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The use of CAD CAM For Fixed Partial Prostheses

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The use of CAD CAM For Fixed Partial Prostheses

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بسم الله الرحمن الرحيم

وَقُل رَّبِّ زِدْنِي عِلْمًا

"O my Lord! Advance me in knowledge."

TaHa (20:114) سورة طه

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Declaration

I, Nawaf Mohammed Almustafa, hereby declare that I am the author of this thesis and that all the references cited have been consulted by myself. I was the principal investigator in all studies described in this thesis. This work has not previously been submitted for a higher degree in this or any other university.

Nawaf Mohammed Almustafa

Certificate

I hereby certify that Nawaf Mohammed Almustafa has fulfilled the conditions of Ordinance 39 of the University of Dundee and is qualified to submit this for Doctor of Philosophy.

Professor David Ricketts

Certificate

I hereby certify that Nawaf Mohammed Almustafa has fulfilled the conditions of Ordinance 39 of the University of Dundee and is qualified to submit this for Doctor of Philosophy.

Professor Graham Chadwick

To my parents and my wife

Thank you very much for your support without you this would not have been possible

MAY GOD BLESS YOU ALL

Abstract

Due to the increasing demand from patients and dentists for highly aesthetic and strong, metal-free restorations there has been a rapid increase in research into dental CAD CAM technique and zirconia based restorations over the last decade. Such new technology has the potential to take the place of conventional techniques and materials for fabricating indirect dental restorations in the future.

In this PhD thesis, five laboratory studies were designed to investigate zirconia bridges constructed using dental CAD CAM. The studies concentrated on:

1. Ideal force applied by dentists for cementing zirconia bridges and the impact on seating.

2. The effect of firing cycles and zirconia thickness on the fit of zirconia bridges.

3. The effect of span length on the fit of three and four unit all zirconia bridges.

4. The effect of veneering on the strength of three unit zirconia bridges.

5. The fit of three unit all zirconia bridges produced by digital and conventional techniques.

For these laboratory studies an ideal three unit (and four unit for study 3) fixed-fixed all ceramic bridge preparation was carried out on two plastic teeth and all SLA models and zirconia based bridges were made using the Lava COS and Lava™ CAD CAM system (3M, ESPE).

In addition to the laboratory studies, a clinical audit was carried out to assess satisfaction (dentist, dental technician and patient) with zirconia based restorations (through a

series of questionnaires) made and fitted at Dundee Dental Hospital and School. In addition, as part of this audit a simple cost analysis was carried out to explore the differences in cost between zirconia based restorations and high fusing gold alloy based metal ceramic restorations.

Four of the studies (studies 1, 2, 3 and 5) investigated the internal and marginal fit of the zirconia based restorations under differing laboratory and clinical procedures and conditions. It was found that the seating force used to cement a zirconia based bridge had no impact upon fit (Study 1). Whilst the thickness of zirconia (all-zirconia bridge and un-veneered zirconia framework) did not affect the fit of the restoration, veneering the framework did lead to a statistically significant deterioration in fit (Study 2). Although leading to a poorer fit veneering did have a positive effect in strengthening the zirconia framework, but neither un-veneered nor veneered frameworks were as strong as monolithic/all zirconia bridges (Study 4). Despite the high shrinkage during post milling sintering and the potential for greater distortion on longer span bridges, the longer span bridges investigated in Study 3 did not impact upon fit. In study 1, 2, 3 and 4 the Lava COS intra-oral scanner was used to create a digital impression of the tooth preparations and study 5 confirmed that the fit of bridges made from these impressions were better than those made using conventional addition cured silicone putty and wash impressions (Study 5). The results of the questionnaires used in the audit revealed high satisfaction rates with all stake holders and the cost analysis showed that producing zirconia based restorations can be five to six times cheaper than conventional gold based restorations.

Despite the variations in fit which were found in Studies 2 and 5, all bridges produced were within what would be regarded as clinically acceptable and comparable to those produced with more traditional techniques.

Chapter 1

Introduction and literature Review

1.1 General Introduction

Since GV Black's seminal work on Oral Pathology and restoration of teeth (Black, 1917), great focus has been devoted to directly placed restorations, initially with amalgam (Ramesh Bharti et al., 2010) and cohesive gold (Arthur, 1855, Arthur, 1977) and latterly with glass ionomer (Wilson and Kent, 1971), since the acid etch technique was discovered by Buonocore in 1955 (Buonocore, 1955), composite based restorations. However, due to life style changes especially in younger patients, such as increased consumption of carbonated, acidic drinks (Cheng et al., 2009) and the fact that patients are keeping teeth for longer (Watt et al., 2013), tooth wear as well as dental caries have become common place and a major dental problem (White et al., 2012). This has partly led to the increased demands for indirect restorations as well as for more aesthetic restorations. Older directly placed materials, such as dental amalgam, do not have good aesthetics and this does not endear them to an increasingly demanding public (Chadwick, 1988, Chadwick, 1989).

Indirect restorations, made in the laboratory, usually on stone models cast from impressions of tooth preparations, have varied from intra-coronal inlays, onlays, partial to full coverage crowns, and bridges to replace missing teeth (Ricketts and Bartlett, 2011). The type of restoration, its functional and aesthetic demands, will dictate which material or combination of materials it is made of.

1.2 Indications for indirect dental restoration

Aesthetics, function, speech, occlusal stability, periodontal splinting, feeling of completeness, orthodontic retention, protecting weakened teeth (as a result of caries, endodontic treatment, trauma and tooth wear) and restoring occlusal vertical dimension are the main reasons and indications for restoring and replacing missing teeth with indirect restorations (Blair et al., 2002). Indirect restorations are not only classified as to whether they are intra-coronal or extra-coronal and how much tooth coverage occurs (full coverage crown versus three quarter crown for example) but also by what material is used in its fabrication (all metal (noble (precious) versus base (non-precious)), metal ceramic, all ceramic and composite).

Whilst this thesis will mainly address bridges (fixed partial prostheses/dentures), the discussion in relation to crowns can equally apply to conventional bridge retainers and the terms will be used interchangeably throughout.

1.3 Dental materials used for indirect dental restoration

1.3.1 All metal indirect restorations

Full crowns in metal are widely used in the posterior region as aesthetic demands are less and they require minimal tooth preparation which makes them a less destructive restoration choice compared to those made from other materials (all ceramics and composite) or combination of materials (metal ceramic) (Blair et al., 2002); this is largely due to the strength of the metals in thinner sections. Some of the major characteristics of most metals and alloys are that they are hard, ductile and good conductors of both heat and electricity. However material selection for all metal dental restorations will depend on many factors such as cost, corrosion and tarnish, castability and handling, physical properties, biocompatibility and the ability to resin bonding (Wassell et al., 2002c).

Noble (precious) versus base (non-precious) metals

The metal elements used in indirect dental restorations can be divided into noble or precious metals (e.g. gold, platinum, palladium, rhodium, ruthenium, iridium and osmium), and base or non-precious metals (e.g. nickel, chrome and cobalt). Noble metals are elements which are very resistant to corrosion, unlike the base or non-precious elements which are susceptible to oxidisation (corrosion) in moist environments.

Gold is one of the oldest materials used to directly fill tooth cavities, because pure gold is soft and malleable, making it easy to form and shape by cold working with gold foil (Liviu Steier et al., 2007). However, today gold is rarely used in dentistry as a pure metal (Knosp et al., 2003) as its properties make it unsuitable for casting into indirect restorations as it has a low proof stress (the load per unit area that a structure can withstand without being permanently deformed by more than a specific amount (0.2 % (30 MPa)) and a large elongation (the length at breaking point expressed as a percentage of its original length (i.e. length at rest) (45.0 %)) (Knosp et al., 2003). To overcome these problems other elements are added to gold in varying quantities to give a range of gold alloys with slightly different properties making them suitable for various clinical applications. Such improvements in properties arise from changes in the basic crystal lattice of the alloy as a consequence of the inclusion of other elements.

Alloys used in dentistry are a mixture of two or more metallic elements and are classified according to the percentage of the major elements they contain (gold, palladium, silver, nickel, cobalt, chrome or titanium) (Anusavice et al., 2012) as well as their intended clinical application (ISO Standard 8891:2000).

Nobel (precious) metal alloys

Noble metal alloys consist of more than 75.0 % of the noble elements in their composition (Anusavice et al., 2012). They are often called precious metal alloys because the noble elements are expensive and this can cause some confusion in dental terminology.

Today four types of gold casting alloys exist, (low strength, medium strength, high strength and extra high strength) which are classified according to the percentage content of noble metals (Table 1.1) (ISO Standard 8891:2000). The percentage of gold drops when moving from type 1 (soft) to type 4 (extra high strength), leading to an increase in hardness, proportional limit and strength, but with a concomitant decrease in ductility and corrosion resistance (Knosp et al., 2003, McCabe and Walls, 2008). Noble metal alloys can be cast into relatively thin sections of 0.3 to 0.5 mm (Shillingburg, 1997), and can achieve a high degree of casting accuracy and hence fit and longevity. As such this has made noble metal alloys the "gold standard" restoration historically against which newer materials and modes of manufacture are compared.

In addition to the afore mentioned properties, as dental materials are in contact with the oral tissues for many years, it is important to choose alloys with minimum biological risk This means that the materials should have low release of elements (corrosion), which can be achieved by using noble metal alloys (Wataha, 2000). Gold alloys are (disregarding the few studies reporting allergic reaction to gold and palladium alloys such as (Moller, 2002)), in general, considered to be highly biocompatible, (Wiesenfeld et al., 1984, Ahlgren et al., 2002, Wassell et al., 2002c, McCabe and Walls, 2008, Ahlgren et al., 2014).

Table 1.1 Types of gold alloy, their constituents, usage and gold content percentage based on ISO Standard 8891:2000

Types of gold	Usage	Gold content % (m/m)	Other contents % (m/m)
Type 1 (low strength)	Slight stress (inlays)	80 - 90	Ag, Cu, Ir, Rh, Ru
Type 2 (Medium strength)	Moderate stress (inlays and onlays)	75 - 78	Ag, Cu, Pt, Pd, Zn, Ir, Rh, Ru
Type 3 (High strength)	High stress (Crowns and bridges)	62 - 75	Ag, Cu, Pt, Pd, Zn, Ir, Rh, Ru
Type 4 (Extra high strength)	Very high strength (partial dentures frameworks and bridges)	60 - 70	Ag, Cu, Pt, Pd, Zn, Ir, Rh, Ru

Palladium was used to produce a cheaper replacement to gold in the 1930s known as white gold. White gold was widely used as a dental casting alloy, mainly when the price of the gold increased in the early 1970s (Nitkin and Asgar, 1976, Bessing, 1988). White gold is rarely used in dentistry today because the prices of palladium have also increased (Van Noort, 2013).

Base metal alloys (non-precious)

Base metals alloys contain a very low percentage (≤ 25.0 %) of noble or non-noble metals in their composition (Anusavice et al., 2012). There are three groups of base metal alloys depending on the materials used, namely cobalt chrome (Co/Cr), nickel chrome (Ni/Cr) and titanium. Cobalt chrome consists mainly of cobalt (35.0 – 65.0 %), chromium (25.0 - 35.0 %) and molybdenum (4.0 %) whilst nickel chrome mainly consists of nickel (61.0 – 81.0 %), chromium (20.0 %), molybdenum (4.0 %) and beryllium (4.0 %). Both types of base metal alloy (Co/Cr and Ni/Cr) contain smaller amounts of other materials such as silicone and carbon which contribute to the mechanical and physical properties of the alloys (improved casting, handling, ductility, hardness and strength) (Anusavice et al., 2012). Because of their increased strength base metal alloys can be cast to a thickness as low as 0.2 mm (Shillingburg, 1997) with satisfactory long term clinical function.

Base metal alloys are widely used for metal ceramic restorations and can be used for all metal dental restorations, however, some of the constituents are considered to be toxic and/or can cause allergic reactions in some patients. The main known allergic reaction is caused by nickel which can lead to contact dermatitis. To overcome this nickel free base metal alloys are available and have been used widely (Magnusson et al., 1982, Hildebrand et al., 1989, Staerkjaer and Menne, 1990, Wassell et al., 2002c, McCabe and Walls, 2008).

Titanium is well known for its biocompatibility. However, casting titanium requires high temperatures and special investment and consequently it is not commonly used for customised bespoke dental restorations (Ida et al., 1982). Therefore its use is mainly limited to pre-formed post, crowns, frameworks and dental implants (Kikuchi and Okuno, 2004). Whilst titanium has been used to create metal based indirect dental restorations using a spark erosion technique, studies are few and its use has not taken off commercially (Nakaoka et al., 2011, Özcan and Hämmerle, 2012).

1.3.2 Metal ceramic crowns

Metal ceramic crowns/bridge retainers are the most commonly used type of crown or retainer, because they combine both the strength of the metal framework and the aesthetics of the veneering ceramic (Ku et al., 2002, Zarone et al., 2011).

When it comes to choosing a metal alloy for the core (coping) of the metal ceramic restoration, its coefficient of thermal expansion is very important, because if there is a large mismatch between the metal alloy and the veneering ceramic, expansion and contraction on heating and cooling will result in stress generation within the ceramic and crack formation leading to catastrophic fracture of the ceramic (Combe et al., 1999, McCabe and Walls, 2008, Bonsor and Pearson, 2013). The melting temperature of the metal alloy is also important, because if it is too close to the firing temperature of the ceramic, melting of thin sections of the coping or deformation can occur. Most of the metal alloys available for all metal dental restorations can be used when constructing metal ceramic dental restorations as even the majority of noble metal alloys have a high fusing (melting) point as compared to the firing temperature of the ceramic (Combe et al., 1999, McCabe and Walls, 2008, Van Noort, 2013).

To ensure optimum aesthetics when making a metal ceramic crown, an opaque ceramic is needed to mask the metallic appearance of the coping beneath the veneering ceramic (Combe et al., 1999, McCabe and Walls, 2008, Bonsor and Pearson, 2013). However, to allow for the thickness of the metal alloy coping, the opaque ceramic and the veneering ceramic, the tooth has to undergo a heavier preparation, than that required for all metal restorations, in the order of around 1.5 to 2 mm where metal and ceramic coverage is required (Blair et al., 2002).

1.3.3 Veneering Ceramics and its techniques

Constructing a dental ceramic restoration in the laboratory is time consuming and requires high skills to achieve satisfactory results with respect to strength and aesthetics. After constructing the coping or framework whether in metal or some form of ceramic, a veneering ceramic layer should be applied over it, which is mainly responsible for aesthetics; the core or framework confers strength upon the restoration. There are two methods for veneering frameworks or copings, these are the layering and the pressing techniques (Miyazaki et al., 2013).

Layering technique

The layering technique (conventional/ traditional) is considered to be the most commonly used veneering technique, for restorations within the aesthetic zone or smile line. This technique gives greater control over the aesthetics of the restoration where dentine and enamel shades can be built up incrementally to mimic natural tooth tissues. First, the frame work or coping is covered by an opaque ceramic to mask the dark shine through of metal (if metal ceramic restoration) or coloured to form an appropriate base colour (if zirconia at its pre-sintered stage). If masking a metal framework the opaque layer is either left to dry or placed in a furnace to speed up the drying process (Schweitzer et al., 2005).

Following this, the selected shades of veneering ceramic are built-up by hand. The dentine and enamel ceramics (feldspathic ceramic) consist of a powder which is mixed with distilled water to form a creamy paste. The dentine shade is applied first using a vibration technique to allow the powder to settle with no voids and using absorbent paper to remove excess water. The consolidated powder can then be carved to the shape of the dentine, incorporating anatomical features such as mamelons and then the enamel ceramic can be added in a similar fashion. The ceramic build-up is made larger than the desired final restoration in order to allow for shrinkage (10.0 to 20.0 %) caused by condensation and the firing/sintering procedures. Until the ceramic is sintered the powder liquid mass is still fragile and should be handled with care (Bonsor and Pearson, 2013).

Following sintering in the furnace, the ceramic crown contour can be adjusted and before glazing, stains can be used to produce a more detailed final restoration, marking up stained pits and fissures, lamellae or hypoplastic spots for example. Finally, a glaze layer is applied in order to produce a smooth shiny surface to the restoration. For this purpose, a low fusing transparent glass ceramic is painted in thin layers on the outer surface of the dental restoration which is then returned to the furnace to produce the glaze (Griggs, 2007, Bonsor and Pearson, 2013).

Pressing technique

The pressing technique uses the lost wax approach similar to that used in casting metal restorations. First, the metal frame work with opaque ceramic (Schweitzer et al., 2005) or the coloured zirconia framework undergoes a wax additive process to contour the final restoration. This is then sprued and invested in a refractory investment, which, once set, is placed in a furnace to allow burnout of the wax leaving a space for the ceramic to fill. A mono-colour leucite ceramic ingot is then melted/softened at high temperature (around 1000° - 1180° C) in a furnace and then slow pressure is applied via a plunger in order to press the ingot into the void created after de-waxing the framework. Once removed from the furnace and cooled the investment is then sectioned and the restoration carefully removed, cleaned, coloured and glazed/polished.

The pressing ceramic is not translucent and only few shades are available which makes it difficult to produce a highly aesthetic dental restoration using this technique. However, once the pressing procedure is finished, the buccal pressed ceramic can be cut back and a conventional feldspathic ceramic can be used to produce a better aesthetic (shade and translucency) dental restoration (Griggs, 2007, Chadwick and Hall, 2011, Bonsor and Pearson, 2013).

1.3.4 Bonding ceramics to metal alloys

Bonding ceramics to metal alloys relies on an intimate contact between the ceramic and the metal alloy coping. This can be achieved by one of three mechanisms:

Mechanical retention: this occurs usually as the ceramic flows into the micro-spaces created in the surface of the metal alloy during the fabrication process. In addition, air abrasion using alumina (25.0 – 30.0 µm) and/or grinding can increase the surface roughness to maximise the mechanical interlocking (Chadwick and Hall, 2011, Bonsor and Pearson, 2013, Van Noort, 2013).

Compression fit: this technique depends mainly on the difference in the coefficient of thermal expansion between the two materials (the metal alloy and the veneering ceramic). As most ceramics have a coefficient of thermal expansion that is lower than the metal alloys, the metal alloy will contract more than the ceramic on cooling and as a result the ceramic will be placed under compression. The shrinkage of the ceramic will also enable adaptation to the irregularities within the metal surface. The coefficient of thermal expansion of the metal alloy and the veneering ceramic should however be similar or near to each other to avoid undue stress within the ceramic (Chadwick and Hall, 2011, Bonsor and Pearson, 2013, Van Noort, 2013).

Chemical bonding: In order for a chemical bond to be achieved, an oxide layer is required. The oxide layer formed on the metal surface then chemically bonds to the oxide layer formed on the opposing ceramic. Compatibility of the metal and ceramic is a must for this bond to happen. The elements that can be used to form oxides include gallium, indium, zinc and tin, as well as the base metals which have been widely used for this purpose because they produce thick oxide layers. In the case of noble metal alloys, the coping or framework is returned to the furnace at a specific temperature and a partial vacuum to allow an oxide layer to be formed via the elements mentioned which are added to the alloy. The oxidising process needs to be precise because the cohesive bond between the oxide layer and the ceramic might fail if the oxide layer is too thick (Bonsor and Pearson, 2013, Van Noort, 2013).

1.3.5 All ceramic dental restorations

The high demand for tooth coloured, aesthetic indirect restorations has seen the development of a wide variety of all ceramic restorations and modes of manufacture (Table 1.2), with carefully colour matched and characterised ceramics being able to accurately reproduce the natural appearance and translucency of the tooth (Fischer and Marx, 2002, Griggs, 2007). Whilst providing excellent aesthetics, ceramics suffer from significant draw backs namely their inherent weakness and brittleness (Park et al., 2008) and potential for wear of the opposing dentition by unglazed, adjusted ceramic (Hmaidouch and Weigl, 2013). Whilst these drawbacks have led to the gradual development of different types of ceramic and manufacture there are still some contraindications for the use of such restorations, for example, patients with para-functional habits such as bruxism, limited inter-occlusal distance mainly in cases of over erupted opposing teeth, worn short crowns and deep over bites (Conrad et al., 2007).

Table 1.2 Ceramic development in the last century

Year	Invention
1889	First PJC (patent)
1900s	PJC, feldspathic ceramic (introduced)
	50 Years
1950s	Metal ceramic crowns
1960s	Aluminous Dicor ceramic (Castable)
1965	Aluminous porcelain
	20 Years
1980s	Empress I, Vita (pressable)
1989 to 1994	In Ceram, Alumina, Spinell, Zirconia, All Ceram (first CAD CAM) material & CAPTEK (first generation)
1998	Empress II
2006	Monolithic Lithium Disilicate
2009	Monolithic Zirconium
2013	Nano-Ceramic

Porcelain jacket crowns (PJC)

Porcelain Jacket Crowns are one of the oldest all ceramic crowns, that were introduced before bonding ceramics to tooth structure was possible. However their use was restricted mainly to the anterior teeth due to the relatively poor physical properties of porcelains at the time (Magne et al., 2010, Chadwick and Hall, 2011). These crowns were made of feldspathic ceramics, and whilst highly aesthetic, they were very fragile and prone to fracture. **Feldspathic ceramic** is composed mainly of oxide components (SiO_2, Al_2O, and Na_2O). Potassium and sodium feldspars are naturally occurring elements composed mainly of potash (K_2O), soda (Na_2O) and alumina (Al_2O). A glass phase is formed when potassium feldspar is fired to high temperatures and the material undergoes expansion. Leucite, which has a high coefficient of thermal expansion, is added to control the thermal expansion (Van Noort, 2013).

In order to overcome the low material strength, the ceramic in practical use had to reach a thickness of 1.5 to 2 mm, and as a result the tooth preparation was relatively excessive (Blair et al., 2002, Ricketts and Bartlett, 2011) in order to accommodate this. Traditionally, the die of the prepared tooth (for PJC) was covered with a burnished platinum foil, the purpose of which was mainly a supporting matrix for the ceramics while building-up the PJC and during the firing process (Bonsor and Pearson, 2013). The platinum foil was then removed from the fit surface before cementing the dental restoration with a non-adhesive luting cement, typically a zinc phosphate (Yu et al., 2014).

Due to the inherent weakness of the PJCs a twin (platinum) foil technique was introduced. The first platinum foil served the same purpose as the one platinum foil technique and was removed following firing, however a second platinum foil which was laid down over the first was left in place to support the ceramic restoration, acting as a core and increasing the strength while cemented in the mouth (McLean et al., 1976, Moffa, 1988).

A number of foil techniques followed on from platinum foil and work carried out by McLean and Sced in 1987, showed that to resist ceramic fracture a minimum foil thickness of 0.1 mm should be reached (McLean and Sced, 1987).

Alumina

In an attempt to further increase the strength of PJCs, in 1965 McLean introduced **aluminous porcelain** to dentistry (McLean and Hughes, 1965). Aluminous porcelain had a higher strength compared with feldspathic porcelain and was used as a coping material onto which feldspathic porcelain could be added. Because of the higher strength of the aluminous porcelain, crack propagation from any micro cracks formed in the more superficial feldspathic porcelain is prevented. Originally alumina was added to feldspathic porcelain but due to its opacity could only be added up to 45.0 – 50.0 % before it affected the overall appearance of the crown (McLean, 1997). The fired alumina core and aesthetic feldspathic porcelain veneer became the standard to produce PJCs, but despite the increase in flexural strength it was not recommended for posterior teeth (Wassell et al., 2002c).

Dentine bonded crowns

Whilst developments in relation to strengthening ceramics, but maintaining their aesthetics continue, in the early to mid-1990's the dentine bonded crown was described which achieved its strength from being bonded to the entire underlying tooth structure or composite core (Burke, 1996). In this way any micro cracks that occur in the ceramic are prevented from propagating leading to catastrophic failure (Burke, 1995). This is because such cracks propagate from within the crown outwards to the surface (Chadwick and Hall, 2011). The dentine bonded crown developed from the adhesive technology which was used to cement ceramic veneers. Such crowns consist of a ceramic whose fit surface can be etched with hydrofluoric acid to create a micromechanically retentive surface. Bonding to the ceramic is also facilitated through application of a silane coupling agent. The luting cement used to fit the crown is a dual cured composite resin luting cement which is bonded to the tooth via a compatible dentine bonding agent (Burke, 2007).

1.4 Ceramics

Keramos is the Greek word and origin of the word Ceramic which means 'potter's clay or burnt stuff'. Ceramics are man-made materials which are the result of mixing and "burning" together different metallic and non-metallic elements (McCabe and Walls, 2008, McLaren and Cao, 2009). Oxygen unions with metals or semi-metal elements, usually aluminium, calcium, magnesium, sodium, zirconium and silicone, produce metal oxides that are the main components of ceramics (McCabe and Walls, 2008). The terms ceramic and porcelain are often used interchangeably, however, ceramic is the overall term given to the main group of materials of which porcelain is a specific example containing Kaolin, Quartz and Feldspar (Ferracane, 2001). To use the term dental porcelain would therefore be inappropriate because the dental ceramics contain no or little kaolin (Bonsor and Pearson, 2013).

Ceramics have been used in dentistry for more than 200 years, the first being introduced to dentistry by a French dentist called De Chemant in 1789 (Miyazaki and Hotta, 2011). In 1808 an Italian dentist Fonzi invented “terrametallic incorruptibles” ceramic teeth, which were held in situ using platinum pins or frames. By 1903 Dr. Charles Land presented the first dental ceramic crown and, in 1963, the first commercially available dental ceramic was introduced by VITA Zahnfabrik (Kelly et al., 1996, C. Â. M. Volpato et al., 2010, R. Narasimha Raghavan, 2012).

1.4.1 Dental ceramic composition

Ceramic on its own is weak, opaque and porous, which makes it unsuitable for dental applications (McCabe and Walls, 2008), because dental restorations made out of pure ceramic are easy to fracture as a result of cracks developing during the fabrication process in the laboratory (McLean, 2001). Different types of minerals (quartz, silica (flint) and feldspar (potassium-aluminium silicate)) are therefore blended together to produce stronger and more translucent materials for dental use (McCabe and Walls, 2008).

Dental ceramics can be used for different purposes and depending upon their application, clay (kaolin), silica, binder (feldspar) and glasses can be blended in different ratios to produce high-fusing and low-fusing dental ceramics (Ferrancane, 1995, Combe et al., 1999, McCabe and Walls, 2008).

1.4.2 Ceramic properties

Ceramics found their way into dentistry and were considered a material of choice due to their low cost and ready availability as well as:

1. Biocompatibility
2. Abrasion resistance
3. Stain resistance
4. Stable colour
5. White in colour and can be pigmented to match any dental shade

Despite these ideal properties ceramics, suffer from inherent brittleness and much work has been done to overcome this, such as building up the restoration on thin metal copings or alumina cores mentioned previously in Section 1.3.5 in order to prevent crack propagation. The next section further explores the different types of ceramics that have been developed for dental use.

1.4.3 Classification of dental ceramics

Today, many types of dental ceramics are commercially available, with each ceramic having different physical properties, clinical use and production method. As a result they have been classified in different ways in the literature. Some publications classify dental ceramics according to the type of ceramic (feldspathic, aluminous, glass infiltrated aluminous, glass infiltrated spinel and glass ceramics) (McLean, 2001), firing (fusing) temperature (High > 1300° C, medium 1101° - 1300° C, low 850° - 1101° C, ultralow < 850° C) (Anusavice et al., 2012), substructure material (glass ceramic, CAD CAM ceramic, sintered ceramic core) (Kelly et al., 1996) and fabrication technique (castable ceramics, pressable ceramics and machinable ceramics (CAD CAM)) (Qualtrough and Piddock, 2002). A recently updated International Standard (ISO 6872: 2015 Dentistry – ceramic Materials) classifies them according to cementation, minimum mean flexural strength and chemical solubility (Table 1.3).

For the purpose of this thesis the different types of ceramic will be classified according to fabrication technique as this fits with the work undertaken in this thesis.

Table 1.3 Porcelain-classification and performance limits (ISO 6872: 2015 Dentistry- Ceramic Materials)

Class	Recommended clinical indications	Cementation (A = Adhesive, N = not adhesive)	Minimum mean flexural strength (MPa)	Chemical Solubility (μg/cm²)
1a	Monolithic single unit anterior crowns, veneers, inlays and onlays.	A	< 50	< 100
1b	Coverage of ceramic or metal framework	A	< 50	< 100
2a	Monolithic ceramic for single unit anterior/ posterior restorations. Fully covered substructure ceramic for single unit anterior/ posterior prostheses	A	> 100	< 100
2b	Fully covered substructure ceramic for single anterior/posterior prostheses	A	> 100	< 2000
3a	Monolithic ceramic for single-unit anterior/posterior prostheses and for 3 unit prostheses not involving molars	A/N	> 300	< 100
3b	Fully covered substructure for single-unit anterior/posterior prostheses and for 3 unit prostheses not involving molars	A/N		< 2000
4a	Monolithic ceramic for 3 unit prostheses with molars	A/N	> 100	< 100
4b	Fully covered substructure for 3 unit prostheses with molars	A/N		< 2000
5	Monolithic ceramic for prostheses involving 4 or more units or fully covered substructure for prostheses involving 4 or more units	A/N	> 800	< 100

Powder/liquid ceramics

Conventional ceramics are presented in a powder/liquid form and include glass ceramics and glass/crystal ceramics which are often used as veneering ceramics for all ceramic and metal frameworks. Feldspathic and alumina ceramics are examples of powder liquid ceramics which have been discussed in section 1.3.5.

Whilst Section 1.3.5 describes the conventional use of an alumina core made from a powder liquid build up, a newer technique called **slip casting** has also been used to produce an alumina strengthened coping, the original In-Ceram (Vita Zahnfabrik). Its use in dentistry was described in 1989 by Sadoun (McLean, 2001). The terminology slip casting should not be confused with the casting method traditionally employed in the lost wax technique; it more accurately describes a powder/liquid technique.

In-Ceram Alumina® (Vita Zahnfabrik) ceramic consists mainly of a partially sintered alumina interconnecting framework infused with lanthanum glass. In this process, the alumina particles are mixed with water to produce a "slip" which is painted over an absorbent gypsum die of the prepared tooth. The water from the slip is then absorbed by the gypsum die due to capillary action, condensing the alumina particles against the die. The alumina particles are then partially sintered together to form an interconnecting mesh into which lanthanum is infused, producing a dense coping with good physical properties onto which veneering ceramic can be built (Kelly et al., 1996, McLean, 2001).

A further modification of the powder/liquid technique has been used to generate high alumina reinforced crowns or **Procera All-Ceram** (Procera-Sandvik, Stockholm, Sweden). In this technique high-purity alumina particles are dry pressed over an over-sized die of the prepared tooth. The oversized die is manufactured by scanning a conventional stone model of the tooth preparation, the data obtained being sent electronically to a dental laboratory in Sweden where an enlarged copy die is milled; the enlargement being carefully calculated based upon the sintering shrinkage of the material. The compacted and now unsupported alumina core is then sintered at 1550° C for one hour (McLean, 2001). The high alumina coping produced is then returned to the referring laboratory for veneering with aesthetic ceramic (Qualtrough and Piddock, 2002).

This section has explored how conventional alumina cores, All-Ceram and In-Ceram slip casting have been used to produce modified alumina cores of increased strength (Neiva et al., 1998) and in some cases used for bridges as well as single unit crowns (Kelly et al., 1995, McLaren, 1998).

Castable ceramics

Dicor (**D**entsply **I**nternational & **COR**ning glass (DENTSPLY International Inc, York, Pa.)) which consists of tetrasilicic fluormica crystals, was the first commercially available castable ceramic that could be used to manufacture indirect restorations using the lost wax technique (Adair and Grossman, 1984, Grossman, 1985, Malament and Socransky, 1999). This crystal structure imparted strength and fracture resistance to the restoration by virtue of their flexibility and plate like form which could interfere with crack propagation (McLean, 2001). Because Dicor restorations are monochromatic, their shade and characterisation had to be achieved with surface colourant glass of approximately 50.0 to 100.0 µm thickness (Kelly et al., 1996). However, this wore down over time with concomitant deterioration in the aesthetics. To overcome this, for restorations in the smile line, the Dicor crowns were often cut back to allow for a veneering feldspathic ceramic with the resultant restoration being called a Willi's glass crown (Geller and Kwiatkowski, 1987).

Despite claims of increased strength, Dicor was still considered to be relatively weak and its use was recommended for inlays only (McLean, 2001). However, in a study of 1444 Dicor restorations, Malament and Socransky (1999) showed that after 16 years, the survival of the restorations could be improved by acid etching the fit surface of the restoration and bonding the crowns down to prepared dentine with resin luting cement. At 14 years the same authors estimated that the survival rate of Dicor etched restorations was between 71.0 to 75.0 %, with tooth position being the greatest influencing factor; highest failure rates in second molar teeth and lowest on incisor teeth (Malament and Socransky, 1999). Earlier laboratory work on dentine bonded crowns also showed that Dicor crowns were significantly stronger under compressive loading compared with either feldspathic or aluminous ceramic dentine bonded crowns (Mak et al., 1997).

Pressable ceramics

One of the main disadvantages in the manufacture of conventional ceramic restorations is the high degree of shrinkage on firing. Pressable ceramics overcome this to a degree and are presented as glass ceramic ingots which are similar in composition to powder/liquid ceramics. However; they contain less porosity and are more crystalline in content. In this technique, the ceramic ingots are heated to a specific temperature where they start melting and become a viscous liquid, after which they are forced under pressure to fill a cavity in a refractory mould (lost wax technique) (Bonsor and Pearson, 2013). The shrinkage that occurs when the crown has formed is mainly due to contraction on cooling which is readily overcome/counteracted by the expansion of the investment material (Kelly et al., 1996). Full details of the pressing process are described in chapter 3 (2^{nd} laboratory study) as this technique is used in the work presented in this thesis.

IPS-Empress® and IPS-Empress®2 ceramics are examples of pressable ceramics. They consist of leucite-reinforced and lithium disilicate reinforced glass ceramics respectively. The leucite and lithium disilicate reinforces the glassy matrix and aids in preventing crack propagation. The melting point of IPS-Empress® is 1180° C and that of IPS-Empress® 2 is 920° C. SEM analysis of the two materials show that the leucite crystal content of IPS-Empress® is higher than the lithium disilicate content in IPS-Empress®2 (70.0 % and 35.0 % volume respectively) with the latter having more elongated and interlocking crystals. It is these structural differences which result in the IPS-Empress® 2 having superior mechanical properties; its flexural strength for example is three times that of IPS-Empress® (Holand et al., 2000).

Because the IPS Empress ingots are monochromatic, the coping formed needs to be veneered with aesthetic ceramics to produce a more detailed final indirect dental restoration (McLean, 2001, Qualtrough and Piddock, 2002). Both types of Empress can be readily etched for use as dentine bonded crowns.

IPS-Empress® ceramics is now called IPS E max®, where lithium oxide is added to the alumina-silicate glass, It delivers outstanding aesthetics, precision fit and strength (Shenoy and Shenoy, 2010).

Machined processed crystalline systems

More recently, Computer Aided Design Computer Aided Manufacturing (CAD CAM) technology has been introduced to dentistry and has become a practical fabrication option for indirect dental restorations. This technology was first introduced for milling fully sintered ceramic blocks, however, its use has now been expanded and can be used to mill semi-sintered ceramics which subsequently undergo heat treatment to ensure full sintering (Denry and Holloway, 2010). CAD CAM technology consist of three stages; first the scanning (in the laboratory or intra-orally), 3D designing (CAD) via computer software and, finally, milling of the dental restoration (CAM). As a result of using CAD CAM technology, designing and fabrication of dental restorations can be completed within hours, which allows the patient to receive their dental restoration the same day (one appointment dental restoration). Consequently, a new class of ceramics was developed for use with CAD CAM systems, namely machinable glass-ceramics. Examples of ceramic materials available for the CAD CAM technology are: Silica based ceramics, infiltration ceramics and oxide high performance ceramics (Beuer et al., 2008c).

Silica based ceramics

There are several types of **Silica based ceramic blocks** available for the construction of dental restorations using CAD CAM technology (Vitablocs Mark II (Vita), IPS e.max CAD (Ivoclar Vivadent), Vitablocs TriLuxe (Vita) and IPS Empress CAD Multi (Ivoclar Vivadent)). Besides the availability of monochromatic ceramic blocks, multi-coloured layered ceramic blocks are also provided by some manufacturers (e.g. IPS Empress CAD Multi (Ivoclar Vivadent)), the latter being used mainly when fabricating fully contoured anatomical crowns in the smile line (McCabe and Walls, 2008).

Infiltrated ceramics

An example of an **Infiltrated ceramic** blocks that can be used for CAD CAM systems is Vita In-Ceram, which has the same composition as the conventional In-Ceram ceramics (Beuer et al., 2008c). Vita has produced three types of ceramics that can be used with CAD CAM technology:

In-Ceram Alumina VITA, this ceramic is based on the original powder/liquid material that was described in Section 1.3.5. Since 1999, condensed partially sintered blocks of this material have become available for milling (Tinschert et al., 2001a, Apholt et al., 2001, Chaar et al., 2015). Its use is suitable for anterior and posterior crown copings and anterior three unit bridges (Vult von Steyern et al., 2001, Beuer et al., 2008c).

In-Ceram Zirconia (Vita) ceramic was initially developed as a powder/liquid ceramic in the same way as In-Ceram alumina, however, partially stabilised zirconium oxide (35.0 %) was added to the original In-Ceram alumina powder producing a porous partially sintered framework into which glass can infiltrate. Partially sintered blocks of this material, suitable for milling, have also been available since 1999 (Apholt et al., 2001, Tinschert et al., 2001a, Chaar et al., 2015). The addition of the zirconium oxide led to an increase in the flexural strength of the material enabling it to be used in the manufacture of three unit bridges as well as single unit restorations (Wagner and Chu, 1996, Chong et al., 2002, Guazzato et al., 2002, Raigrodski, 2004, Yilmaz et al., 2007, Miyazaki et al., 2013, Chaar et al., 2015).

In-Ceram Spinell (Vita), this material again is based upon the In-Ceram alumina however, in this material, magnesia is added to the alumina coping material which subsequently undergoes glass infiltration (Conrad et al., 2007). The addition of the magnesia makes the In-Ceram Spinell much more translucent (Heffernan et al., 2002a, Heffernan et al., 2002b), so unlike the In-Ceram alumina and zirconia it is not suitable for use over discoloured teeth. Whilst the flexural strength of In-Ceram Spinell is not as good as that of In-Ceram alumina or zirconia (Magne and Belser, 1997, Chaar et al., 2015) its translucency makes it ideal for use in highly aesthetic single unit anterior crown copings on vital teeth and in young patients (Beuer et al., 2008c).

Oxide high performance ceramics

Oxide high performance ceramic blocks suitable for milling in the CAD CAM process include aluminium oxide (e.g. In-Ceram AL Block (VITA)) and zirconium oxide (e.g. Lava Frame (3M ESPE), Everest ZS und ZH (KaVo), In-Ceram YZ (VITA)). These materials offer restorations of superior strength (flexural strength and fracture toughness) compared to other all ceramic restorations. Aluminium oxide blocks have been recommended for use as copings for anterior and posterior crowns and bridges in the anterior region (Beuer et al., 2008c) and due to the superior physical properties of the zirconium oxide blocks can also be used for bridges and implant abutments both in the anterior and posterior region (Komine et al., 2010).

1.5 Zirconium

Zirconium dioxide (ZrO_2), is a new material that has become popular over the last decade, as an aesthetic ceramic that can be used to replace metal alloys when constructing indirect dental restorations (copings and frameworks). In addition to aesthetics, zirconia has superior mechanical properties, mainly its high flexural strength and fracture toughness (Denry and Kelly, 2008). Zirconium dioxide ceramic is also biocompatible, making it also suitable for medical use, mainly in total hip replacement (Christel et al., 1988).

Zirconium in a pure state does not exist in nature. It is a hard metal that resists corrosion, the same as steel (Piconi and Maccauro, 1999). In 1789, zirconium dioxide (ZrO2) was discovered by a German chemist Martin Heinrich Klaproth. Subsequently, in 1824, Jons Jakob Berzelius (a Swedish chemist) was the first to produce impure zirconium metal by heating a mixture of potassium and potassium fluoride (Piconi and Maccauro, 1999). It was not until 1914, that pure zirconium was isolated and the first commercially produced zirconium was made available in 1925 by Van Arkel and De Boer (Haynes, 2011-12).

Temperature associated changes in zirconia structure

Between room temperature and temperatures up to 1170°C, zirconia is found in its monoclinic phase. When it is heated up to between 1170°C and 2370°C, the structure changes to the tetragonal phase and when heated further the structure enters the cubic phase (Figure 1.1) (Denry and Kelly, 2008).

$$\text{Monoclinic} \xrightarrow{\boxed{1170°}} \text{Tetragonal} \xrightarrow{\boxed{2370°}} \text{Cubic}$$

Figure 1.1 The effect of temperature on zirconia

On cooling zirconia in the tetragonal phase, to room temperature, it returns to the monoclinic phase and this is accompanied by a large increase in size which can lead to fracture of the material.

The use of zirconia for fabrication of dental restorations

Dental zirconia frameworks used with CAD CAM systems are **Y**ttria **S**tabilized **T**etragonal **Z**irconia **P**oly-crystal (Y-TZP)(Komine et al., 2010). Usually, ytrria (Y_2O_3) is added to zirconia when it is in its tetragonal stage, this results in stabilizing the (tetragonal) zirconia when cooled to room temperature, leading to so called “transformation toughening” of the ceramics and the production of a material with high fracture toughness and resistance to crack propagation (Figure 1.2, Figure 1.3) (Beuer et al., 2008c, Denry and Kelly, 2008, Komine et al., 2010). Such zirconia can be presented and milled in different forms (green, pre-sintered and fully sintered forms).

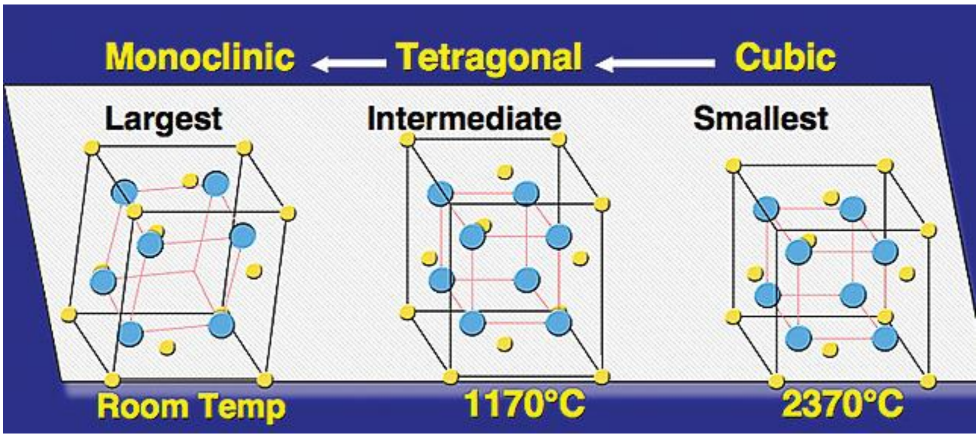


Figure 1.2 transformation toughening of zirconia

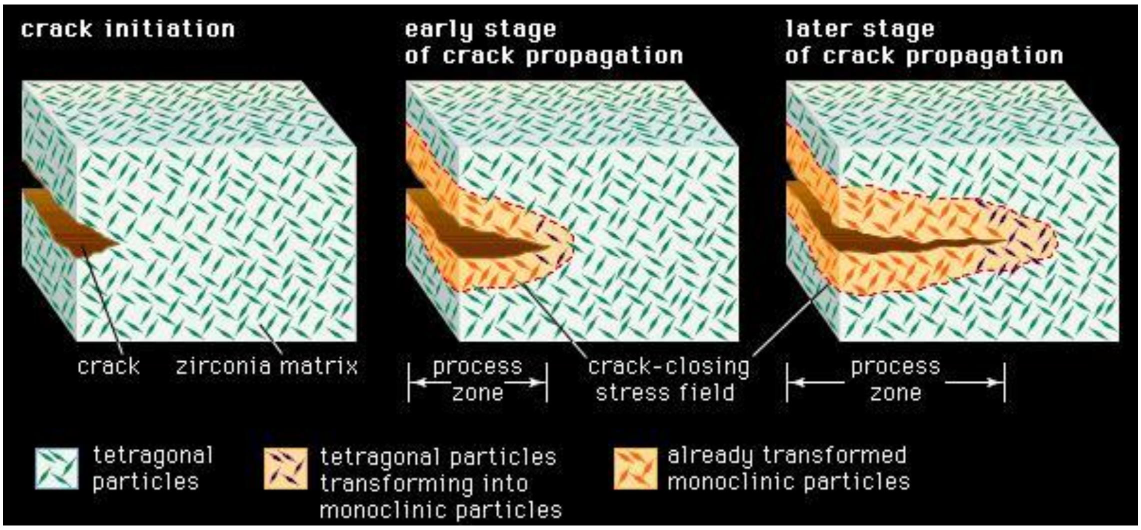


Figure 1.3 Resistance to crack propagation (courtesy of http://www.britannica.com/)

Zirconia blocks or ingots produced by different manufacturers for the use with CAD CAM technology differ slightly in their composition. They also come in different sizes and shades depending on the CAD CAM system and the dental application (McLaren and Cao, 2009, Miyazaki and Hotta, 2011).

1.5.1 Stages when zirconia milling can take place

Zirconia blocks available for CAD CAM restorations can be presented in different forms based upon the level of sintering.

Green Stage

Blocks in the **green stage**, have undergone no sintering and consist of compressed zirconia powder and binding agents (Beuer et al., 2008c). As such they are soft and are easy to mill, causing less wear to the milling carbide burs and require no water coolant (Beuer et al., 2008c, Komine et al., 2010). Their inherent weakness however makes them susceptible to breakage in the manufacturing process. Copings and frameworks are then fired and undergo approximately 25.0 % shrinkage which has to be accounted for in the CAD process (Beuer et al., 2008c).

Pre-sintered (white stage)

Pre-sintered blocks have undergone a partial sintering heat process leading to approximately 5.0 % shrinkage of the material. The blocks at this stage have no binder and are rather porous still (Beuer et al., 2008c). Milling of zirconia blocks in the pre-sintered form is carried out either dry with carbide burs or wet (coolant) with diamond burs (Reich et al., 2005a). Again softness of the material means that milling leads to little wear of the milling burs, but the pre-sintering process ensures that the milled restorations are more robust. The milled restoration is then further sintered undergoing an approximate 20.0 % shrinkage, again accounted for in the CAD software.

Fully sintered

Blocks of fully sintered zirconia can also be milled and have the advantage that no sintering and hence shrinkage has to be accounted for. Milling fully sintered zirconia blocks requires water coolant and diamond burs. Although their use has the advantages mentioned they have some disadvantages namely a more robust milling machine is required (high rigidity and stability), a longer milling time is needed, there is high wear of burs and milling fully sintered zirconia can lead to stresses formation within the material which leads to cracks formation and fracture of the restoration (Tinschert et al., 2001a, Tinschert et al., 2001b).

1.5.2 Survival of zirconia

The goal of prosthodontic treatment is to restore aesthetics, speech and function. Metal ceramic indirect dental restorations have been used for over 50 years (Sundh et al., 2005), which makes them, to date, the preferred dental restoration, due to their proven track record. Despite this, failure can occur due to clinical problems such as caries or due to technical problems such as fracture, aesthetics, or ceramic chipping (Tartaglia et al., 2011).

In recent years aesthetic restorations (all ceramic) have become more popular, therefore researchers have started focusing on and comparing the new all ceramic material to the metal ceramics, mainly regarding fit, survival and success rates (Sailer et al., 2007b, Gonzalo et al., 2009).

Both metal ceramic and zirconia restorations should be durable. That is they should demonstrate survival and success. The survival of a restoration means, that it continues to function in the mouth even if it suffers some minor problems. Success is when the restoration survives in an intact anatomical shape, function and aesthetics (Potiket et al., 2004, Agustín-Panadero et al., 2014).

Studies on the survival rate of dental zirconia restorations are summarised in Table 1.4, most of them being on bridges. It is clear that observation periods range from 1 to 13 years, zirconia bridges have greater complications compared to zirconia single crowns (Agustín-Panadero et al., 2014), as there is less studies on zirconia single crowns.

As zirconia oxide is opaque, a crown core constructed of this is made aesthetic by applying a translucent feldspathic ceramic veneer on the top of the zirconia core.

Although, the ceramic veneer improves the appearance of the zirconia restoration, the studies in Table 1.4 show a high rate of veneer fracture (chipping). The amount of veneer fracture ranges from 6.0 % to 15.0 % in the period of between 3 to 5 years (Agustín-Panadero et al., 2014). This is higher than the values of veneer fracture in metal ceramic restorations which is said to be around 4.0 % (Tan et al., 2004). Veneer fracture can be as a result of a weak bond between the zirconia and the feldspathic veneering ceramics.

In contrast, a 10 years prospective study of metal ceramic dental restorations, followed a total 466 restorations. It concluded that metal ceramic restorations have good longevity, but just like veneered zirconia restorations, the main problem was with fracture (cracking or chipping) of the veneering porcelain overlying the metallic core (Reitemeier et al., 2013).

Chipping of veneering ceramic is more common that delamination from zirconia based restorations, and to minimize this risk full contour zirconia restorations can be constructed (Burke et al., 2013), this is mainly because aesthetic, all-zirconia restorations can now be produced.

Comparing the zirconia based restoration outcomes and survival rates with metal ceramic dental restorations, as mentioned earlier, it can be seen that the same factors affect both types of restoration. However, even with fracture of the veneering porcelain zirconia restorations will continue to appear more aesthetic, compared to metal ceramics as the latter are more likely to exhibit shine through of the metal core (Magne et al., 1999).

Table 1.4 Summary of longevity studies of zirconia based ceramic restorations

Study	Number of restoration	Observation Period	Restoration type	Findings	Survival
(Suarez et al., 2004)	18	1 year and 6 months	Bridges	0 chipping	100.0 %
(Vult von Steyern et al., 2005)	20	2 years	Bridges	3 chipping	100.0 %
(Raigrodski et al., 2006)	20	3 years	Bridges	5 chipping	100.0 %
(Sailer et al., 2007a)	57	5 years	Bridges	1 chipping, 1 bridge fracture	73.9 %
(Edelhoff et al., 2008)	22	3 years	Crowns & bridges	1 chipping	90.0 %
(Molin and Karlsson, 2008)	19	5 years	Bridges	1 re-cement	100.0 %
(Tinschert et al., 2008)	65	3 years	Bridges	4 chippings, 2 adhesive fracture	100.0 %
(Beuer et al., 2009c)	21	3 years	Bridges	1 fracture, 1 re-cement	90.5 %
(Sailer et al., 2009)	36	3 years	Bridges	9 chipping	100.0 %
(Schmitt et al., 2009)	30	3 years	Bridges	3 chipping	100.0 %
(Schmitter et al., 2009)	30	2 years	Bridges	1 chipping, 2 adhesive fracture	96.6 %
(Wolfart et al., 2009)	24	4 years	Bridges	3 chipping, 2 adhesive fracture	96.0 %
(Beuer et al., 2010)	18	3 years	Crowns & bridges	5 chipping, 1 bridge fracture	88.2 %
(Roediger et al., 2010)	99	4 years	Bridges	13 chipping, 6 adhesive fractures	94.0 %
(Tartaglia et al., 2011)	473	3 years	Crowns & bridges	chipping	100.0 %
(Pelaez et al., 2012)	20	4 years	Bridges	2 chipping	100.0 %
(Burke et al., 2013)	41	5 years	bridges	8 chipping	97.0 %
(Rinke et al., 2013)	99	7 years	Bridges	19 chipping, 7 adhesive fracture, 12 bridge fracture	83.4 %
(Haff et al., 2015)	33	13 years	Bridges	3 chipping, 1 re-cement	91.0 %
(Konstantinidis et al., 2015)	27	3 years	Bridges	8 chipping	83.0 %

1.6 CAD CAM

Dentists have for many years been technology focused. As regards the fabrication of indirect restorations in the 1980s Computer Aided Design Computer Aided Manufacturing (CAD CAM) (Beuer et al., 2008c) was introduced to the profession which potentially permits such restorations to be fabricated at the chairside. With advances in computing such technology has since become popular and is considered to be one of the most practical and convenient methods for fabricating dental restorations.

CAD CAM technology is likely to take over from conventional chairside and laboratory techniques in the future, for it offers high precision restoration production at a lower unit cost facilitated by a new generation of computer literate, digitally and technologically minded dentists and technicians. Such advances have already been seen with a big leap in dental radiography, towards digital imaging (Wenzel and Gröndahl, 1995) and cone beam CT technology (Brullmann and Schulze, 2015), as well as changes in computerized medical records and digital dental photography (Desai and Bumb, 2013).

1.6.1 History of dental CAD CAM

The first application of CAD CAM technology was initiated and described by Duret and Preston, the pioneers of dental CAD CAM technology, in the early 1970s (Duret and Preston, 1991). In this early system, the tooth preparation was scanned using an intraoral digitizer (optical impression) allowing a 3-D graphic to be reconstructed on a computer monitor. This in turn allowed virtual design (CAD) of the morphology of the indirect dental restoration (crown) by application of editable software and the construction from a ceramic block of the restoration with the aid of a numerically controlled milling machine (CAM).

A dental CAD CAM system was first produced commercially for the first time by Duret and co-workers called Sopha® (Sopha, bioconcept, France) (Duret and Preston, 1991, Miyazaki et al., 2009). However, it was not widely available, because of its complexity and cost (Mantri and Bhasin, 2010). Despite this lack of commercial uptake research in the 1970s and 80s to develop a new dental CAD CAM system based on Duret's system continued (Rekow, 2006).

It was however not until Mörmann, together with the help and knowledge from his friend Dr. Brandestini (an electrical engineer), worked to develop the CAD CAM technology further, that a system could manufacture a tooth-colored posterior indirect dental restoration (inlay) (Mörmann et al., 1989, Miyazaki and Hotta, 2011). The system was called computer-assisted **CER**amic **REC**onstruction, and was known widely as **CEREC**.

The development of dental CAD CAM systems is still continuing with an aim of improving the technology. Although, today there are more systems available in the market (Table 1.5) it is interesting to note that there is as yet no internationally agreed standard for the many CAD CAM systems and interoperability of this technology (R.G Chadwick-Personal communication). The only published ISO standard to date relates to laboratory based CAD CAM scanners (ISO 12836: 2015 Dentistry- Digitizing devices for CAD CAM systems for indirect dental restorations – test methods for assessing accuracy).

Table 1.5 Development timeline of CAD CAM dental systems

Year	Scientist /Systems	Place/company
1970s	Duret and Preston	University of Southern California, USA
1984	Sopha system	Sopha bioconcept.
1980s	Mörmann and Brandestini	University of Zurich, Switzerland
1987	Cerec® 1	Sirona Dental Systems
1989	Precident	DCS Dental, Allschwil, Germany
1993	Procera®	Nobel BioCare, Yorba Linda, CA
1994	Cerec® 2	Sirona Dental Systems
2000	Cerec® 3	Sirona Dental Systems
2001	Cerec® InLab	Sirona Dental Systems
2001	Cercon®	DeguDent, Dent
2002	Everest®	Kavo Dental, Lake Zurich, IL
2002	Lava™	3M ESPE, St. Paul, MN
2008	E4D	PLANMECA, E4D

CEREC dental CAD CAM system

The CEREC system was the first commercially available CAD CAM system. It was able to scan the cavity directly in the patient mouth using a compact intra-oral camera. As a result of the data collected, the design and fabrication of the indirect dental restoration (ceramic inlay) is all made at chairside. Although it was an evolution in constructing indirect dental restorations, it had two limitations. At that time, the system was limited to inlay restorations and secondly the constructed indirect dental restoration had no occlusal morphology (Mörmann et al., 1989). More information about the development of the CEREC system will be introduced in the "CAD CAM systems available" section.

As a result of further research and development, **CEREC** 2 was produced and introduced in 1994; the system gave the user (dentist or technician) more options of dental restorations when compared with CEREC 1. The CEREC 2 system was the same as CEREC 1, displaying the captured data in 2-D. In the new millennium, with all of the upgrades in technology and 3-D systems in dentistry, CEREC saw the need and necessity to upgrade their system. This was when CEREC 3 was introduced to the market.

As regards the milling component, CEREC 1 and 2 were only one-bur-systems, whereas CEREC 3 is a two-bur-system; however, it was not until 2003 when the three dimensional (3-D) virtual editing display was available with CEREC 3 system. As a result of the introduction of the 3-D display to the CEREC 3 system, the design and production of indirect dental restorations became easier, both for the dental office and the laboratory technician (Mörmann, 2006).

1.6.2 CAD CAM components

Whilst there are a number of different dental CAD CAM systems available on the market, in general, they all consist of four components: a scanner (laboratory or intra oral scanner), CAD (3D designing software), CAM (Milling device) and finally a furnace used for semi-sintered zirconia (Miyazaki et al., 2009, Ting-Shu and Jian, 2015) to bring about structured rearrangements and enhance the porcelain physical properties.

Scanning

Scanning is the start point at which the data is collected from a prepared tooth and transferred into 3D digital data that will be used for designing and manufacturing the CAD CAM dental restoration (Beuer et al., 2008c).

Dental CAD CAM scanners are divided into two groups: **laboratory scanners** (used with conventional impressions and stone models) and **intraoral scanners** (digital impression) (Fuster-Torres et al., 2009).

1) Laboratory scanners Laboratory scanners collect data either from the die stone model (Miyazaki et al., 2009) or directly from the impression (depending on the system). When the latter is used it reduces the production time needed, because no pouring of the impression with stone or trimming of models is required. However, scanning dental impressions is still considered challenging, because of the surface points in the depth of the impression, where the light source of the scanner cannot reach. There are two subtypes of laboratory scanners:

(a) Optical scanner or 3D scanner – all such 3D scanners use the same operational principle. They use a light source (laser) (Miyazaki et al., 2009), which is angled in relation to a receptor (sensor); the angulation allows the system to calculate 3-D data of the scanned model in a mechanism known as the 'triangulation procedure' (Mehl et al., 1997, Paulus et al., 2014) (Figure 1.4).

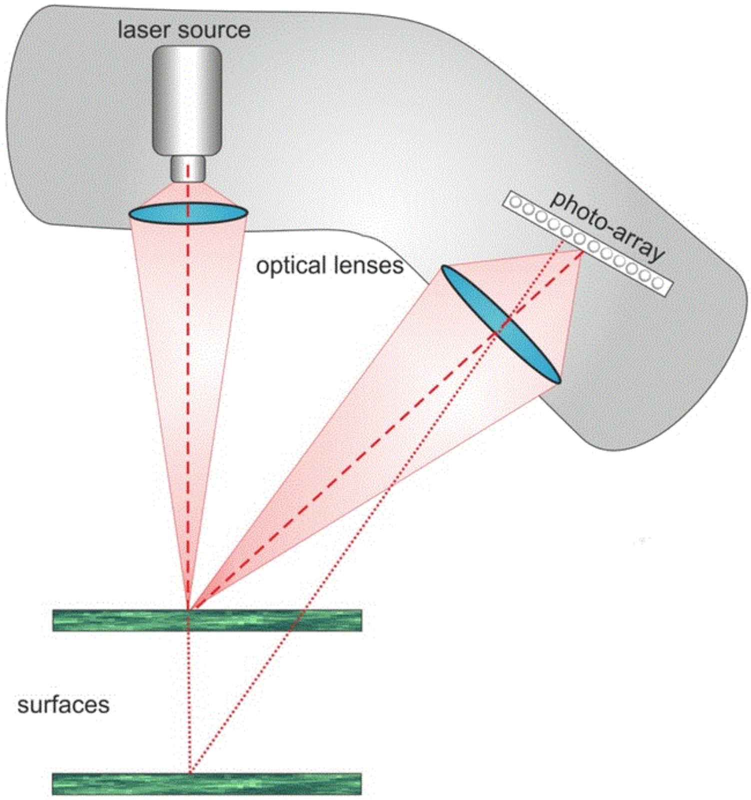


Figure 1.4 The triangulation procedure in optical scanners between the laser source and the receptor sensor (courtesy of Stefan Paulus)

The scanning process is a result of well-defined light lines which are projected by the light source (laser) on the scanned object, the line angulation is based on the distance between the camera and the light source (laser), to allow the camera to capture all details from the scanned model of the prepared tooth. Having more than one camera improves the accuracy by covering more areas and angulations. A motion system supporting several axes holding and positioning the scanned model (teeth) towards the light source is necessary. Each light line resembles a 3D contour line, hence the multiple 3D contours. The scanning head moves in a precise linear axis when the light source is a laser (multiple lines), whereas the scanning head is fixed with a white light scanner (several shifted line patterns from a central position). As mentioned previously, multiple cameras and a multi-axis stage can increase the scanning accuracy, by allowing to scan in different angulations, which will lead to more accurate 3D data. Occasionally problems occur while scanning, but with this technology it is possible to re-scan the impression or model more than once to overlap and cover all of the areas. The collected data can then be converted into a 3-D virtual dental die model, using design software (CAD) which can be analyzed and edited to design and finish a virtual dental restoration that fits perfectly in/on the prepared tooth (Beuer et al., 2008c, Miyazaki et al., 2009). All scanners have a built-in PC which needs to be upgraded every 2-3 years, to be able to cover all high demands in relation to scanning.

A variant of the optical scanners are those that employ photographic methods. In this one or more cameras (still images or video capture) with a light source (laser) are used, to collect information of the prepared teeth (Miyazaki et al., 2009). The collected data are again transferred and analyzed by a specially designed software program, to produce a 3D model.

(b) Mechanical scanner this is the other scanning system (method) used. In this method, the stone model is scanned using a fine ball “contact probe”(Persson et al., 1995); the probe head should be very fine to allow for the capture of every fine detail in the prepared tooth. Mechanical scanners are considered very accurate, but they require longer scanning times to produce the virtual 3D model. In addition, it requires very complicated mechanics, which makes it very expensive (Beuer et al., 2008c, Miyazaki et al., 2009). The only example of a commercial mechanical scanner is the Procera scanner from Nobel Biocare.

2) Intra oral scanners collect the data of the tooth preparation directly from the patient's mouth, allowing immediate designing and production of the dental restoration (Mattiola et al., 1995, Reich et al., 2005b) if desired. Intra oral scanners are considered to be a very accurate scanning method by some (Patzelt et al., 2014b), which minimizes the dental clinic steps, obtaining an impression and helping reduce discomfort and the feel of gagging for the patient (Christensen, 2009, Logozzo et al., 2014).

Three technologies are used in intraoral scanners. They, like the laboratory scanners either use the 'triangulation' technique where a light pattern stripe is projected over the object and is reflected back onto a sensor. The projected ray and reflected ray distances are measured by the software, and since the sensor has a fixed angle to the rays, the focal distance and dimensions can be calculated using special algorithms, for example as in the CEREC scanner (Figure 1.5)(van der Meer et al., 2012).

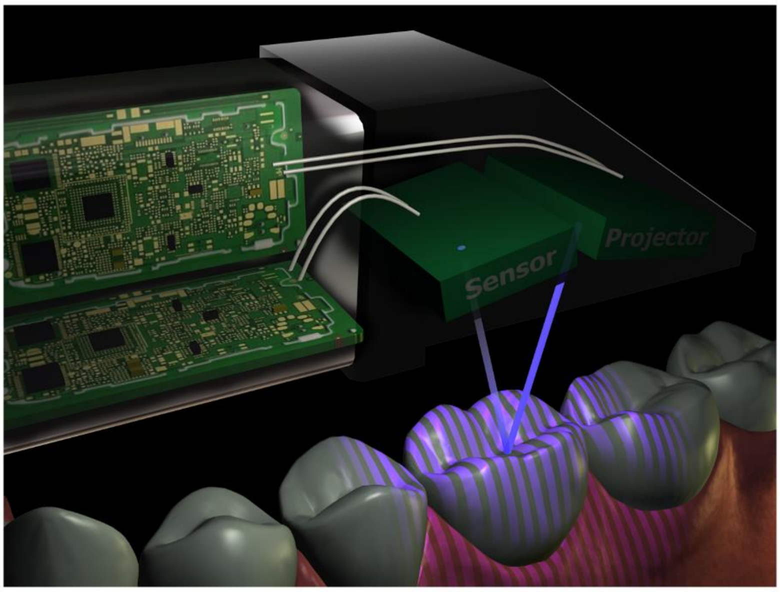


Figure 1.5 Triangulation scanning (courtesy of van der Meer)

The second technology uses 'confocal laser scanning', where a red laser beam is projected over the object. The laser is reflected from the object and fed through a focal filter, to ensure that only the image in the focal point is subsequently reflected on the sensor. Again the focal distance is known. The process requires adjustment of a lens to ensure the object being scanned is in the focal trough of the device e.g. iTero (Figure1.6)(van der Meer et al., 2012).

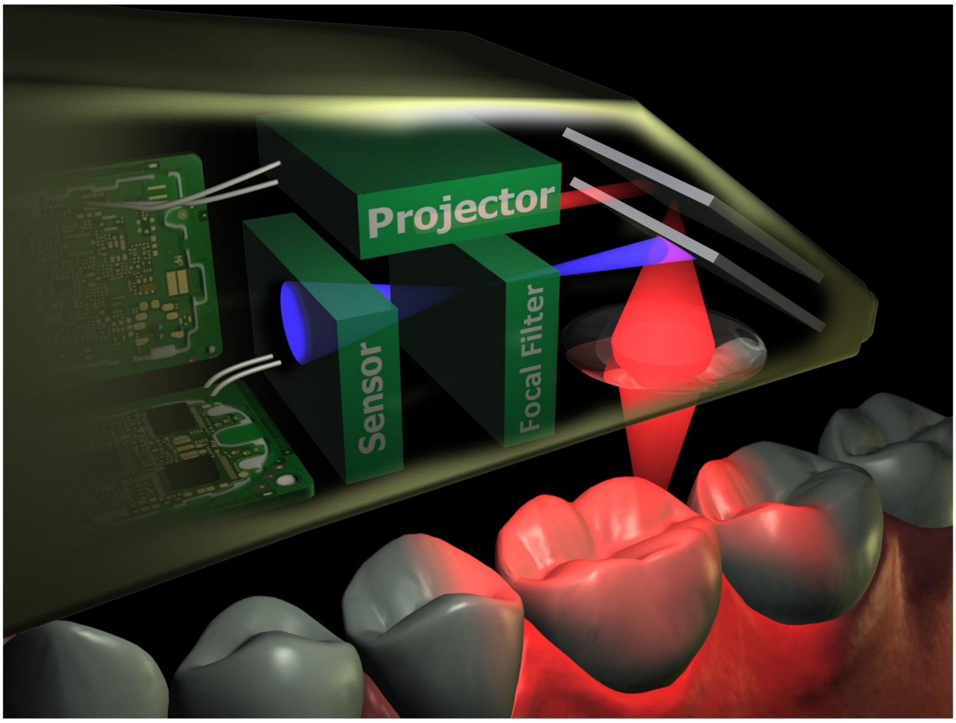


Figure 1.6 Confocal laser scanning (courtesy of van der Meer)

The final device uses the 'active wave-front sampling' technique. This utilizes a 3D video system (20 X 3D frames/Sec), through which the reflected image is fed through a multiple lens system, to project it onto the sensor. Just as for the other technologies, the focal distance is measured, and once the image is in focus the sensor starts to collect the data. If the image is out of focus, this means that the object is away from the lens and a blurred image is constructed using a mathematical estimation formula as in the Lava COS scanner (Figure 1.7)(van der Meer et al., 2012).

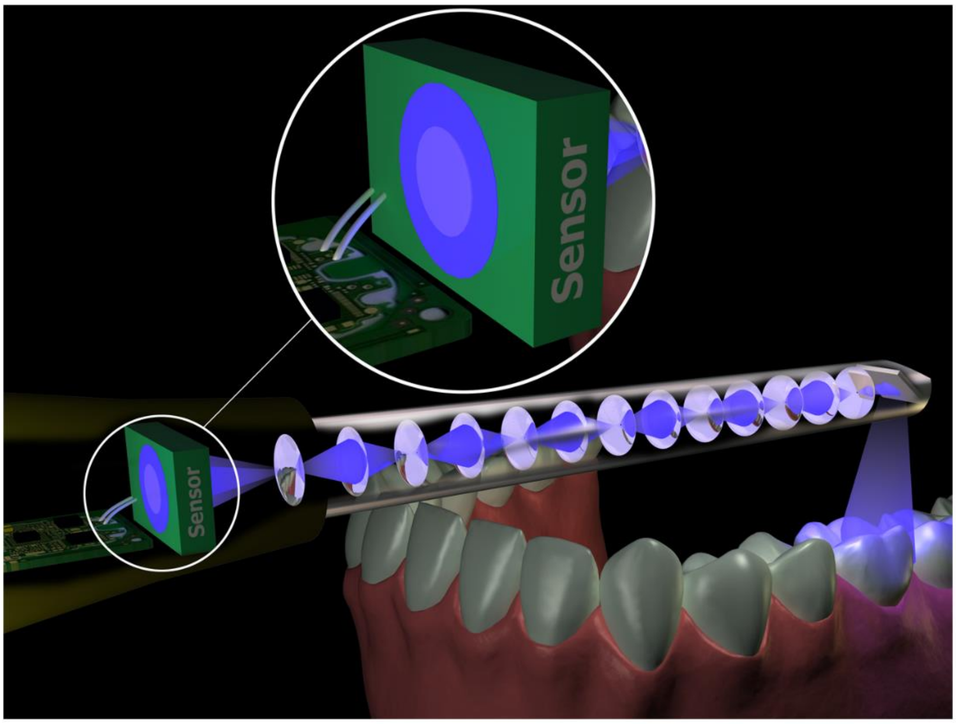


Figure 1.7 Active wave-front scanner (courtesy of van der Meer)

Regardless of the type of intraoral scanner, different materials exist in the oral cavity (dentine, enamel, amalgam and composite) and each one has different light reflection properties (Logozzo et al., 2014). In order for the intra oral scanner to capture the required information, a non-reflective powder is used by some companies for their systems that uses video capturing and blue LED (e.g. Lava, 3M ESPE, CEREC AC) to provide a uniform reflective surface, making capturing an easy and quick procedure (Patzelt et al., 2014b). As these powders contain Titanium dioxide (TiO_2) particles a secondary function, useful when stitching together multiple scans into one image, is that they provide reference points to permit the assembly of such data into one image(R.G Chadwick- personal communication). Not all systems however require the use of non-reflective powder, such as the systems that use laser technology in scanning and measuring the distances (E4D, iTero).

During scanning, the practitioner should ensure that the finish line and margins of the prepared tooth are clear and easily captured by the scanner; a retraction cord or paste can be used to make the margins clearer, but it should be removed or washed away before the scanning process. A large number of intra oral scanners are available from different companies as summarized in Table 1.6.

The quality of the final CAD CAM restoration depends greatly on the accuracy of the scanner, so the scanning procedure should be very precise in recording, the margins, undercuts, contact points, adjacent teeth, gingiva, and opposing dentition (Kohorst et al., 2011).

Table 1.6 Shows different intra oral scanner available in the market

Intra oral scanner	Manufacturer	Image type	Light source
CEREC®	Sirona Dental System GMBH	Multiple images	Blue light
iTero	CADENT LTD	Multiple images	Red laser
E4D	D4D TECHNOLOGIES, LLC	Multiple images	Laser
Lava™ C.O.S	3M ESPE	Video	Pulsating blue light
IOS FastScan	IOS TECHNOLOGIES, INC.	3 images	Laser
DENSYS 3D	DENSYS LTD.	2 images	Light
DPI-3D	DIMENSIONALPHOTONICS INTERNATIONAL, INC.	Multiple images	Light
3D Progress	MHT S.p.A. (IT) and MHT Optic Research AG	3 images	----------------
directScan	HINT - ELS GMBH	Multiple images	---------------
Trios	3SHAPE A/S	Multiple images	---------------

Accuracy

Most companies do not disclose how accurate their machines are and do not mention how they measured the accuracy (Vlaar and van der Zel, 2006); it is mainly determined in studies and research carried out after the machine is released for commercial use. However recently a new ISO standard was published to assess the accuracy of laboratory scanners (ISO 12836: 2015 Dentistry- Digitizing devices for CAD CAM systems for indirect dental restorations – test methods for assessing accuracy) and a standard is being drafted for intraoral scanners assessments of accuracy (R.G Chadwick – Personal communication).

The accuracy of the dental scanners depends highly on their manufacturing quality. Leading manufacturer's scanners usually have and use better production tools and materials. Another factor that can affect the scanner hardware which will affect the scanning accuracy is rough handling, in transporting the machine from one place to another. The scanners should therefore be re-calibrated when they are moved to a new place or even when the temperature is changed, which should be scheduled work, as part of maintaining the scanner. Some companies provide scanners with a calibration block/object, with a known accuracy factor that is higher than the scanner accuracy capability. It is very important to know that the software algorithm cannot calculate and compensate for any temperature effect on the scanner hardware (complex expansion and contraction). Since the scanner contains welding, fasteners and glued sections, and can be used under varying workloads, this explains how important calibration is to maintain accurate scanning results (Hollenbeck et al., 2012).

Another factor that can have an effect on accuracy is the size of the scanner. Larger scanners achieve better results because of their stability and the fact that most of the parts are automated, which will reduce any possible movement and subjective error during the scanning process (Hollenbeck et al., 2012).

Scan Speed and productivity

Scan speed is a very important feature when choosing a scanner, because it will have an effect on the productivity of the dental laboratory, and finishing the case. As with accuracy, there are no standards to compare the scanners and there is no information released from the companies to compare it with any marketing claims. It is claimed that scanning varies from 30 seconds to several minutes (Hollenbeck et al., 2012).

The scan speed alone will not reveal the capabilities of the scanner in terms of productivity. A whole workflow should be considered, starting from creation of the order, scanning, designing and ending with milling the dental restoration. Even if different systems are compared from this point of view, this will result in large performance variation. Usually, fully automated systems allow the user to spend less time on the machine, and on the overall scan process. As mentioned earlier, this reduces human error. Manually processed and controlled systems require more time, because many things need to be adjusted (camera brightness, die position, etc.). Some systems provide a multi-die plate, which reduces the time required to change the dies to compare a single die scanner. This feature allows the operator to use spare time (while the scanner is finishing the scanning process) to design a restoration in the CAD software (Hollenbeck et al., 2012).

The indications for each type of dental scanner are an important factor that needs to be considered along with the speed and accuracy. The indications include long span bridges, dentures and implant abutments, etc. Since there are some cheap low quality scanners which are non-upgradable and support only basic indications which will limit the work that can be produced.

The CAD software will also limit the type of restoration that can be produced. Therefore, this makes it more convenient to have the scanner and the CAD software from the same system, because the developer will integrate more options which will offer a better and more optimized workflow (Hollenbeck et al., 2012).

CAD

Each Company provides its own and unique software that can be used to design different dental restorations using 3D technology (Beuer et al., 2008c). The CAD software has a pre-loaded library including different designs of crowns and bridge frameworks, full anatomical crowns and bridges, inlays and onlays. Newer software can produce even more types of dental restorations, for example implant abutments, removable partial denture frameworks, and orthodontic appliances. Once the data are uploaded to the CAD software, the laboratory steps will be performed virtually after filling the job order (digital laboratory request). First a virtual die will be generated, followed by die sectioning, then the finish-line will need to be marked and finally designing of the required dental restoration, a step by step detailed information is described in laboratory study 1. The CAD software starts by providing a proposal of the ideal restoration that fits the prepared tooth, in relation to the finish-line, contact point and opposing dentition. Then, the dentist can adjust the restoration (fissures, cusps, etc.).

Previously the companies produced closed software, which is compatible with their system only and cannot be used with any other system. Recently, the manufacturers started to produce an open source program (software) which allowed the use of different scanners with different CAD systems (Miyazaki et al., 2009). Unfortunately, there has not been much published about the CAD software, and each company considers this to be its own secret to protect future development and updates to its software.

File format

The file format produced by CAD software is either **ST**ereo-**L**ithography files or Standard Triangle Language (STL). The STL file are considered to be open files. This type of file format is native to the CAD software, which makes it easy for all of the companies to produce a CAM machine which is compatible with most of the available CAD software. However, some companies have their own file format (proprietary), which makes it only compatible with their milling device (Mehl et al., 1997); but, they are all moving towards the open access format, which can be used with a wider variety of companies and materials (van Noort, 2012). Finally the 3-D virtually designed dental restoration is sent to the milling device as digital data (STL file), where it will be milled to the final dental restoration.

CAM

As in any other fabricating industry, Computer Aided Manufacturing in dentistry is the final step that will lead to the production of the final product. The technology has become sophisticated in regard to both the hardware and software. Nowadays, laboratories tend to purchase the latest technology available for cutting and milling dental materials, because it is assumed that this will reduce the working time and minimize the costs. The milling devices (CAM) can be classified in different ways; the first way is according to the number of movement axes in which the blocks can be trimmed: three, four and five axis (Beuer et al., 2008c, Lesson, 2014).

When creating milling machines, it should consist of three linear axes: a horizontal axis (x), a depth axis (y) and a vertical axis (z) (Figure 1.6). The milling tools move from left-to-right (x-axis) and up- and -down (z-axis), while the disc clamp moves forward-and-backward (y-axis); these movements allows the tip of the milling(cutting) tool to reach any point within the work cube or block. The **three axis** milling device has a limited degree of movement in these three directions only. Because of this, the CAD software calculation of the movements is minimal and defined into X-, Y- and Z- values. As a result of the limited movement, the software will virtually block some areas of the final restoration, because it is not possible for the milling machine to reach to these areas in certain angles. The three-axis milling machine is allowed to turn 180° while processing to finish the milling process of the dental restoration. Milling time is shorter with these milling machines, which is considered an advantage, and they are usually cheaper than the other milling devices (four and five axis). Examples of the three axis milling machines are Lava™ CNC 240 (3M ESPE), inLab (Sirona) and Cercon brain (DeguDent) (Beuer et al., 2008c, Lesson, 2014).

Due to the need for milling both sides of the working blocks, to allow for the creation of a better detailed occlusal and fitting surface of the restoration, a new axis has been incorporated into some milling machines, the fourth axis (a) (Figure 1.6). With the fourth axis in the milling machines, most shapes in restorative dentistry can be created, because the machine is able to cut above the mid-line (occlusal surface) which is also known in the milling industry as the ‘parting line’, and then the block will be flipped around the “a” axis and milling below the same line (fitting surface). As a conclusion, the extra turn allows for greater adjustment of the dental restorations with high vertical dimension such as bridge abutments, long clinical crowns and in implant cases, and a result materials and milling time will be saved. An example of a four axis milling machine is Zeno (Wieland-Imes, Ivoclar Vivadent) (Beuer et al., 2008c, Lesson, 2014).

A fifth axis has been added by some manufacturers the (b) axis; **five axis devices** are just like the three and four axis devices in regard to the primary movements (x, y, z and a), in addition to the possibility of a perpendicular movement to the fourth axis (a) (Figure 1.8). The extra movement allows the milling of extra complicated geometry substructures or full dental restorations and an example of a five axis milling machine is Lava™ CNC 500 (3M ESPE) (Beuer et al., 2008c). Although 4 and 5 axis milling machines can produce more complex dental restorations the quality of the final restoration depends highly on the scanning process.

Usually, the four axis milling machine performs ‘indexed milling’, which includes incremental tilts and pauses along the a-axis, while the tool changes its place of milling. On the other hand, the 5 axis milling machines provides a ‘continuous milling’, as a result of the b axis rotation, which allows the continuous contact of the milling tools with the working block, reducing the working time. However, the bigger milling machines are better than the small ones (Beuer et al., 2008c, Lesson, 2014).

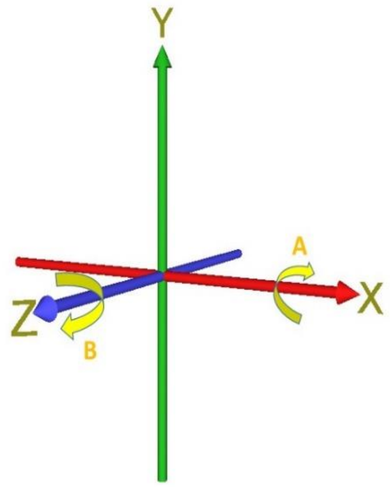


Figure 1.8 The axes of a three (X, Y & Z), four (X, Y, Z & A) and five (X, Y, Z, A & B) axis CAM milling machines

1.6.3 CAD CAM classification

There are different ways to classify the CAD CAM systems, either according to the scanning and production method or according to the milling process.

The CAD CAM systems can be classified into two types depending on their scanning and production device (Mantri and Bhasin, 2010):

1. In-office (chairside): A variety of system permutations come under this heading: only the scanner (intra-oral, e.g. Lava C.O.S), scanner and designing software (e.g. E4D) or having all the components of the CAD CAM system in the clinic (scanner, designing software and milling device, e.g. CEREC system).

2. Dental laboratory: After making the impression (digital or conventional) in the clinic, the remaining production steps (designing and milling) are made in the laboratory. In the laboratory either the laboratory scanner, designing software or the milling device are available in the laboratory, or the scanner and the designing software alone.

The other classification is according to the milling process, either dry or wet. The milling process (dry or wet) depends mainly on the type of materials being milled (Beuer et al., 2008c). Semi-sintered zirconia oxide are mainly used with **dry processing** milling devices, which have several benefits such as: there is no absorption of moisture by the dry zirconia oxide so it can be sintered immediately, and cost effective when it comes to the tools, because less tool wear will occur during the milling process, which makes the milling device cheaper, in addition newer materials which have been introduced can also be dry milled such as resin. An example of dry milling devices are Zeno 4030 (Wieland-Imes, Ivoclar Vivadent), Lava™ CNC 500 (3M ESPE) and Cercon® brain.

The wet processing milling machines are used with fully sintered glass ceramics and metals, where the coolant liquid is used to protect the diamond or carbide cutting burs against overheating while processing the restoration. Usually, fully sintered ceramics are used with wet processing devices, as such the material is milled to the precise size and shape as no subsequent shrinkage in a sintering process takes place. Examples of wet process milling machines include Everest (KaVo), Zeno 8060 (Wieland-Imes), inLab (Sirona).

There are two techniques for producing the final restoration, either subtractive, which is the dominant technology, or the additive technique.

The Subtractive processing technique depends mainly on cutting the material away mechanically (milling) to achieve the desired object. Using this technique allows for the fabrication of sophisticated shapes with a reduced fabrication time (van Noort, 2012). It is however considered to be wasteful as the material removed during the fabrication process cannot be reused. An example of the subtractive processing technique is the Lava (3M, ESPS) milling machine and zirconia blocks(Giordano and McLaren, 2010). In an attempt to save money and reduce the fabrication cost mainly in mass production manufacturer, some companies have moved to the additive manufacturing techniques.

The Additive manufacturing technique is described by the American Society for Testing and Materials (ASTM) as: "the process of joining materials to make objects from 3D model data, usually layer upon layer". In this process the works is created from a series of cross sectional layers, which are printed one on top of the other; to produce a 3D model (object). Using this technique insures that there is no waste of materials. Originally it was called Rapid Prototyping which was introduced in the 1980s to manufacture prototypes and models of objects. Today the additive manufacturing technique allows the production of full scale models, which helps in customizing and modifying the object before producing the final product (Stoker et al., 1992, Kernan and Wimsatt Iii, 2000, Cohen et al., 2009, van Noort, 2012). An example of the additive technique is the production of resin Stereolithographic (SLA) models from computer aided design via 3D printer.

1.6.4 Advantages of using CAD CAM

Dental CAD CAM systems offer advantages when fabricating dental restorations namely (Miyazaki et al., 2009, Beuer et al., 2008c):

1) Improved quality of the final dental restorations (internal and marginal fit).

2) Cost effectiveness (fixed price compared with metals, e.g. gold).

3) Reduced labour and working time.

4) Introduction of new modified dental materials (stronger, dense, and with a superior aesthetics).

1.6.5 Materials available for the use with CAD CAM

Almost all types of fixed (crowns, bridges, implant abutments, inlays and onlays) and removable (removable partial dentures) dental restorations in addition to orthodontic appliances can be constructed using CAD CAM technology.

Different CAD CAM systems are compatible with different types of materials (Table 1.7). Silica-based ceramics, infiltrated ceramics and oxide high performance ceramics (Aluminum Oxide and Yttrium stabilized Zirconium Oxide) are the most widely used materials with CAD CAM technology (Beuer et al., 2008c). The materials are available in blocks and are either mono-chromatic or poly chromatic (Baroudi and Ibraheem, 2015). In addition to ceramics (Table 1.8), metals (titanium, titanium alloys and chrome cobalt alloys), waxes and resin materials may be used with dental CAD CAM systems (Beuer et al., 2008c).

Table 1.7 List of CAD CAM systems, manufacturer and type of materials used

Commercial Name	Manufacturer	Restorations	Materials
Chairside systems			
Cerec 3	Sirona Dental System	Inlays, onlays, Veneers, Crowns	Zirconia, Alumina Oxide, Ceramic, Resin
E4D Chairside	D4D Technologies, L.L.C	Inlays, onlays, Veneers, Crowns, Bridge frameworks, copings	Zirconia, Ceramic, Composite
Laboratory systems			
Cercon	DeguDent GmbH	Crowns, bridges	Zirconia
Cerec MC XL	Sirona Dental Systems	Inlays, onlays, Crowns, bridges, copings	Zirconia
Everest	Kavo Dental Corporation	Inlays, onlays, Veneers, Crowns, bridges	Zirconia, Titanium, ceramic
inLab CAD/CAM	Sirona Dental System	Inlays, onlays, Veneers, Crowns, Bridge frameworks, copings	Zirconia, Alumina, Ceramic
In-Visio DP 3D printer	3D System Corporation		Light cured Resin
Lava	3M ESPS	Crowns, bridges	Zirconia
Neo System	Cynovad	Crowns, Bridges	Resin, Zirconia, Titanium
Perci-Fit	Popp Dental Inc	Crowns, Bridges	Zirconia, Titanium
Procera Forte	Nobel Biocare	Bridges, Copings, Abutments	Zirconia, Alumina, Titanium
Procera Piccolo	Nobel Biocare	Bridges, Copings, Abutments	Zirconia, Alumina, Titanium
Turbodent	U-best Dental Technology Inc	Crowns, Bridges	Zirconia, Titanium
WaxPro	Cynovad	Crowns, Bridges, Copings	Wax

Table 1.8 Shows different types of dental ceramics used with CAD CAM systems

Material name	Material type
Virablocks Mark II	Feldspathic ceramic
Cerec	Feldspathic ceramic
IPS Empress CAD CAM	Leucite re-enforced glass-ceramic
In-ceram Alumina	Glass infiltrated alumina
In-ceram Zirconia	Glass infiltrated alumina with zirconia
Procera	Polycrystalline alumina
Lava Zirconia	Polycrystalline zirconia (Y-TZP)

Ceramic (zirconia) can be used in different stages of sintering (hardness): semi-sintered and fully sintered. At the semi-sintered (green stage) stage, the material is used in a soft stage; during the design and milling the restoration is made over sized, to allow for a shrinkage of around 20.0 – 25.0 % during the sintering (firing) process used to confer superior physical properties. Fully sintered blocks can also be milled with some CAD CAM systems; with this type of density, there will be no shrinkage in the material, which is considered an advantage, because it will reduce the firing cycles and delivery time. However, it takes more time to mill a fully sintered block and will cause more tool wear (Tinschert et al., 2001a, Beuer et al., 2008c). There is therefore a tradeoff between the time for firing cycles for the pre-sintered blocks and the time it takes to mill a fully sintered block, but on balance, the latter is likely to be more time efficient.

1.6.6 Work Flow to construct dental restorations

When a tooth is prepared for an indirect restoration which is to be made using CAD CAM technology, there are two different techniques possible to obtain an impression of the prepared tooth, namely a conventional impression or a digital impression (Miyazaki et al., 2009).

The **conventional** technique usually involves taking an elastomeric silicone impression to produce a working model. Depending on the type of laboratory scanner available, either the elastomeric silicone impression itself or the stone model created from the impression is scanned (Beuer et al., 2008c). This is to collect all of the data needed to design and fabricate the dental restoration.

Alternative, a **digital impression** can be made using an intra-oral scanner. The scan of the prepared teeth together with a scan of the opposing arch can then be mounted on a virtual articulator, using a digital occlusal record. The digital model can then be sectioned virtually to produce the working die. This data can be sent to a production center to order an articulated SLA working model. The models are used during the veneering process of the ceramic framework in order to obtain correct contacts points and occlusion (Beuer et al., 2008c).

After scanning the impression, stone model or using the intra oral scanner, designing the dental restoration using the CAD software and fabricating the final restoration follow the same steps for both techniques. The final dental restoration may either be constructed in the same clinic/dental lab if the milling machine is available or the design can be sent to a production center for fabrication (Figure 1.9).

A step by step scan and design of a dental restoration using the Lava (3M ESPE) is described in laboratory study 1.

Usually, if the material (ceramic) is fully sintered, there are no extra steps required other than finishing (e.g. veneering and glazing) the restoration; however, if semi-sintered zirconia is used, sintering in a furnace is required prior to finishing.

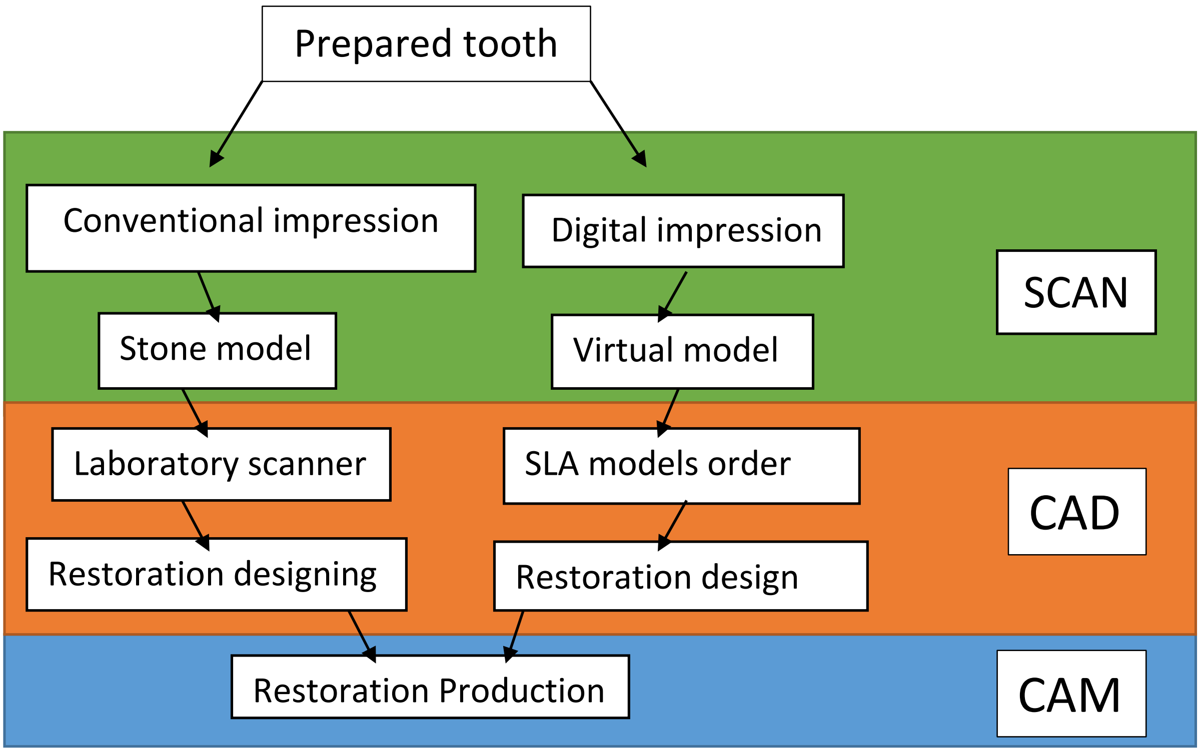


Figure 1.9 Diagram showing the work flow (conventional and digital) for producing a dental restoration using CAD CAM technology

1.6.7 CAD-on veneering technique

Recently a new veneering technique called CAD-on has been introduced to fabricate the veneering layer using Lithium-disilicate (Aboushelib et al., 2008, Beuer et al., 2009f, Kanat et al., 2014a, Kanat et al., 2014b, Torabi et al., 2015b). Some CAD CAM software will allow the fabrication of a two part restoration, a coping and veneering cover. The benefit of this step is that if the ceramic is semi-sintered, both parts are sintered at once, followed by a fusion firing cycle where a connector layer (fusion glass-ceramic) is applied to the inner surface of the veneering ceramic and to the outer surface of the coping. The veneering part is then seated under pressure over the coping, the excess connecting layer removed with a small brush and the two layers fired together to complete the fusion process (Beuer et al., 2009f, Torabi et al., 2015b). When the CAD-on veneering technique was compared with the layering and press-on veneering technique, the results showed that all three veneering techniques led to an increase in the marginal gap of the zirconia based restoration compared with the coping alone; the zirconia coping mean gap was 35.0 µm, which increased to 63.1 µm with the layering veneer technique, 50.6 µm using the pressing technique and finally 51.5 µm with the CAD-on veneering technique (Torabi et al., 2015b). Although all veneering techniques led to an increase in marginal gap all of them produced small marginal gaps and clinically acceptable results.

1.7 Tooth preparation design

The tooth preparation for crowns and conventional bridge retainers involves removing tooth structure to create space for a new restoration and, as such, it is not a conservative procedure. One of the most common complications when preparing teeth is loss of pulp vitality (Saunders and Saunders, 1998, Cheung et al., 2005). Losing pulp vitality can be due to many factors such as the resin-based materials used when restoring teeth for indirect dental restorations, excessive tooth preparation, high exothermic activity of provisional restorative materials and traumatic occlusion due to incorrect restoration occlusal contour (Christensen, 2005). This section discusses tooth preparation, therefore, losing pulp vitality can be reduced or avoided by intermittent cutting and using a high speed hand-piece with plenty of water to reduce the heat and vibration and ensuring definitive restorations are correctly contoured (Ricketts and Bartlett, 2011).

Tooth preparation for indirect full coverage dental restorations is therefore a fine balance of creating sufficient space for the restoration but preserving as much tooth tissue as possible in addition to protecting the pulp and adjacent tooth(Christensen, 2005).

Since tooth preparation for crowns and bridge abutments is an important step to ensure perfect mechanical, biological and aesthetic outcomes of the final restoration, six principles should be considered (Goodacre et al., 2001, Blair et al., 2002):

1. Amount of tooth reduction

2. Finish-line

3. Preparation taper

4. Line angle form

5. Surface texture

6. Retention and Resistance

1.7.1 Amount of tooth reduction

To be able to construct an indirect dental restoration a considerable amount of tooth structure should be reduced during tooth preparation. The type of indirect dental restoration that will be used, will indicate the amount of tooth reduction required which is usually between 0.5 to 2 mm for fully coverage restorations (Ricketts and Bartlett, 2011). There are factors that can affect the amount of reduction for example the position and alignment of the tooth, occlusal relationships, aesthetics, position of the gingival margin, smile line and the tooth morphology (Goodacre et al., 2001).

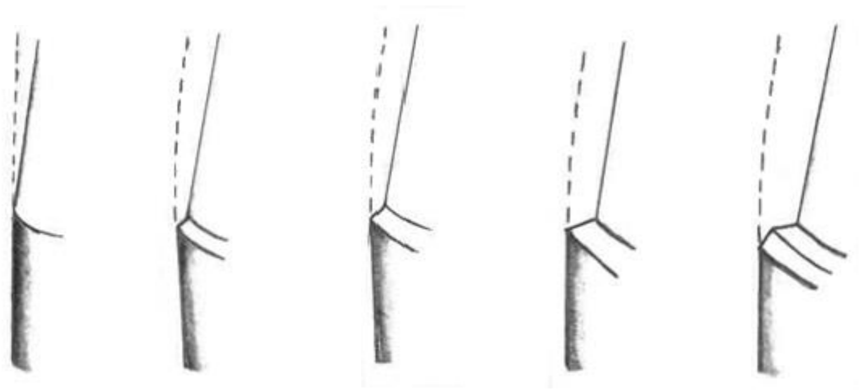
Metal dental castings are very strong in thin sections, which makes a 0.5 mm finish-line depth adequate to construct an all metal dental restoration; this is considered to be the most conservative indirect full coverage dental restoration (Shillingburg, 1997). But because of its color, it is only used for posterior teeth. Porcelain fused to metal crowns used in the aesthetic zone require tooth reduction of between 1.5 to 2 mm; the depth is needed because the metal framework should be covered by an opaque layer of porcelain followed by layering of aesthetic ceramics which helps to achieve a better appearance. Traditional all ceramic (PJC type) crowns, on the other hand, need extensive tooth preparation of around 2 mm all around to provide space for a which is bulk enough restoration to withstand occlusal forces. However, with all of the improvements made to the ceramic materials and bonding to tooth tissue to enhance ceramic strength, 1.5

mm reduction is recommended for all ceramic crowns, which makes the preparation extent similar to porcelain fused to metal crowns (Smith, 1986, Tay, 1992).

1.7.2 Finish-line

Preparing a tooth for an indirect dental restoration requires choosing a finish line. The finish-line form has an influence on crown seating, the thickness of luting material, marginal gap and cementation. The type of indirect dental restoration (all metal, porcelain fused to metal or all ceramic) will indicate the finish-line that will be used.

The most commonly used finish-line designs are: feather-edge, chamfer, deep chamfer, shoulder and shoulder with bevel (Klugman et al., 1978) (Figure 1.10).



Feather-edge Chamfer Deep Chamfer Shoulder Shoulder w bevel

Figure 1.10 Diagram showing different finish lines for crown preparation

Micro-leakage as a result of poor fit and cement dissolution (Jacobs and Windeler, 1991) can cause multiple problems for example pulpal inflammation (Goldman et al., 1992), plaque retention leading to periodontal disease (Valderhaug and Birkeland, 1976) and secondary caries (Valderhaug et al., 1993). However Byrne (1992) and Chan (2004) both stated that the finish-line had no effect on the fitting of a cemented crown (Byrne, 1992, Chan et al., 2004b).

A number of studies have examined the effect of the finish line on the fit of indirect dental restorations (Table 1.9). Different preparation designs of marginal finish-line (feather edge, slight chamfer, deep chamfer, beveled shoulder, and non-beveled shoulder) have been used to study their effect on fracture resistance and their influence on the marginal adaptation of the CAD/CAM zirconia framework. As a consequence of the information gained from these studies, shoulder and chamfer preparation finish-lines are recommended for all ceramic full coverage retainers. In root canal treated teeth that are compromised coronally, a slight chamfer has been recommended (Beuer et al., 2009b, Comlekoglu et al., 2009); this study however, contradicts the findings of another laboratory study which recommended that a shoulder, shoulder with a bevel or heavy chamfer finish-lines can lead to the best marginal fit (Byrne, 1992).

By examining different studies related to the fit of full ceramic crowns or bridges, the most common finish-lines used are shoulder and chamfer (Table 1.9).

Table 1.9 Preparation design (finish-line) for all ceramic crowns

Author and year	Finish-line	Best finish-line
(Bindl and Mormann, 2005)	Chamfer	
(Martin Rosentritta et al., 2007)	Deep shoulder	
(Reich et al., 2008)	Chamfer	
(Beuer et al., 2009b)	Shoulder and Chamfer	
(Beuer et al., 2009d)	Chamfer	
(Kohorst et al., 2010)	Chamfer	
(Comlekoglu et al., 2009)	Chamfer, Mini chamfer, feather-edge, and rounded shoulder	Shoulder Mini-chamfer
(Att et al., 2009)	Deep chamfer	
(Palacios et al., 2006)	Modified chamfer	
(Beuer et al., 2008a)	Shoulder less, Slight deep chamfer, Beveled shoulder, and non-beveled shoulder	Shoulder Chamfer
(Syrek et al., 2010)	Shoulder	
(Lee et al., 2008)	Rounded shoulder	
(Gabbert et al., 2008)	Chamfer	
(Tinschert et al., 2001b)	Chamfer	
(Reich et al., 2005a)	Chamfer	
(Komine et al., 2005)	Chamfer	
(Wettstein et al., 2008)	Shoulder	

The finish line can be located in one of three locations, either supra-gingival, equi-gingival or sub-gingival. The supra-gingival finish-lines are usually recommended, because they have the lowest impact on the periodontium (Silness, 1970). Supra-gingival margins are mainly considered in areas where aesthetics are not of paramount importance and the core is also supra-gingival. Preparing a tooth with a supra-gingival finish-line has additional advantages other than protecting the periodontium, it is easier to prepare, easy to duplicate using impression material (no need for gingival retraction), easy to remove any extra luting cement, easy to clean for the patient and finally, easy to check the integrity of the dental restoration at follow up (Nugala et al., 2012).

It was believed that the equi-gingival finish-line can accumulate plaque which can lead to gingival inflammation and might lead to gingival recession creating a potentially unsightly margin. However, today, this is not thought to be the case, as restorations can be provided with smooth margins and highly polished materials, so the equi-gingival margin is now considered by some to be just as acceptable as the supra-gingival finish-line (Khuller and Sharma, 2009, Nugala et al., 2012).

There are however certain situations when a sub-gingival finish-line is required due to aesthetics and/or restorative considerations (Nugala et al., 2012). With the new developments in dental materials, adhesive dentistry and resin cements, the sub-gingival finish-line can be used where aesthetic demands are high and in the case of discolored teeth; however, this requires perfect tooth preparation and impression, and a well-fitting and contoured restoration to ensure the health of the periodontal structures (Brandau et al., 1988). In cases of short clinical crowns, a subgingival margin can provide greater length of the prepared tooth to increase retention and resistance form (Sharma et al., 2012). It may also be necessary to prepare beyond a subgingival restoration due to an extensive carious lesion or subgingival tooth fracture, or to provide a ferrule for endodontically treated teeth (Sreedevi et al., 2015). When considering the sub-gingival finish-line, the biological width should be respected and the sub-gingival preparation shouldn't exceed half the gingival pocket (0.5 - 1 mm) so as not to disturb the long junctional epithelium or connective tissues, because this is a very important factor for tooth and dental restoration longevity (Nugala et al., 2012).

1.7.3 Retention and Resistance

Retention is defined as that which prevents the dislodgment of a restoration along the path of insertion or long axis of the tooth preparation, whereas **Resistance** is the prevention of dislodgment of the restoration by oblique or horizontal forces.

For a crown to resist dislodgment, it is important to have an adequate occlusal-cervical dimension in relation to the preparation taper (Blair et al., 2002). There is a linear relationship between the preparation taper and the resistance to dislodgment and this is considered as providing the primary retention or resistance form to a crown preparation.

In a study which tested dies with 5, 10 and 15° taper and 3, 4, 6, 8 and 10 mm occlusal preparation height; they found that 3 mm occlusal-cervical height was adequate to provide resistance to dislodgment when the taper was 10° (Woolsey and Matich, 1978). In another study by Maxwell et al. (1990), crown preparations with an occlusal-cervical preparation height of 1, 2, 3, 4 and 5 mm and all with a 6° occlusal convergence angle were compared and again 3 mm height was found to be the minimal occlusal-cervical dimension required to provide adequate resistance to dislodgment (Maxwell et al., 1990).

Secondary retention and resistance forms can be provided if the primary retention is poor, for example in short clinical crowns, by adding boxes, pins and grooves to the preparation. The retention and resistance of a dental restoration are related to the longevity of the restoration (Sharma et al., 2012).

1.7.4 Preparation taper

The preparation taper (convergence angle) refers to the angle between two opposing prepared axial surfaces and is an important feature which gives the prepared tooth its retention and resistance form (see section below on retention and resistance form).

As far back as 1923, Prothero recommended that a taper of 2 - 5° was the optimum when preparing a tooth for a crown (Prothero, 1923, Goodacre et al., 2001). However, this was not subjected to scientific studies until the 1950s when Jorgenson used different taper angles and tested the retention of crowns when tensile forces were applied (Jorgensen, 1955); the results supported the earlier 2 - 5° recommendation by Prothero. Although this was recommended, clinically it is very difficult to achieve and the reported mean convergence angle produced by dentists ranges between 12° and 27° (Noonan and Goldfogel, 1991, Smith et al., 1999). It has also been found that when molar teeth are prepared they have greater preparation taper compared with the anterior and premolar teeth (Annerstedt et al., 1996), which is probably due to the greater difficulty with access and trying to avoid damaging the adjacent teeth.

In 2004, convergence angles ranging from 0° to 70° were studied in different experiments; the optimum retention being obtained was between 2° and 20° with peak retention at 10° (Chan et al., 2004b). Beuer *et al.* also studied the effect of different preparation angles (4°, 8°, and 12°) on zirconia crowns in relation to marginal and internal fit; here, 12° was recommended as the best angle for full ceramic crowns (Beuer et al., 2008b, Beuer et al., 2009b). On balance 12 degrees would appear to be the most appropriate and realistic minimum preparation taper achieved.

1.7.5 Line angle form

The internal line angles are the junctions or meeting lines between prepared tooth surfaces. Usually the line angles produced during the preparation process are sharp, which will lead to stress concentration (Nicholls, 1974). It is recommended that the line angles should be rounded during the tooth preparation to reduce areas of stress concentration especially in relation to all ceramic crowns (Mizrahi, 2008, Ricketts and Bartlett, 2011). A round angle facilitates the laboratory procedure by not trapping air bubbles during fabrication of both the gypsum model and wax pattern, as poor reproduction can adversely affect the fit and seating of the restoration.

1.7.6 Surface texture

After completing the preparation, the surface texture of the prepared tooth should be smooth as this can improve marginal fit (Tjan and Sarkissian, 1986). This having been said some studies have shown that surface roughness can increase the retention of the restoration with certain types of cements (Juntavee and Millstein, 1992). A pragmatic approach may be to use a fine grit diamond bur to at least finish off the finish line to improve fit and leave the rest of the axial walls slightly rougher to maximize retention (Ricketts and Bartlett, 2011).

1.8 Impressions

A summary of the ideal properties of dental impression materials include:

1. Biocompatible, and have a pleasant taste and odour.

2. Fluid enough to flow between the teeth and surrounding tissues.

3. Good working time and long shelf life.

4. Dimensionally stable, and can be disinfected.

5. Compatible with die and cast materials. (Bonsor and Pearson, 2013).

Many materials are available for recording dental impressions and based upon the consensus of opinion from many material text books (Anusavice et al., 2012, Bonsor and Pearson, 2013, Van Noort, 2013) these materials together with their advantages and disadvantages are summarized in Table 1.10.

Table 1.10 Dental impressions, use, advantage, disadvantages and general comments

Material	Use	Advantages	Disadvantages	Comments
Irreversible hydrocolloid	Study models	Rapid set Low cost	Poor accuracy and detail surface	Pour immediately
Reversible hydrocolloid	Study models	Low cost Long working time	Low tear resistance Low stability	Pour immediately with stone
Polysulphide polymer	Most impressions	High tear strength	Messy Unpleasant odour Long setting time	10 mins to set and should be poured within 1 hr
Condensation-cured silicone	Most impressions	Short setting time	Hydrophobic Poor wetting High polymerization shrinkage	Care to avoid bubbles when pouring
Additional-cured silicone	Most impressions	Short setting time Stable	Hydrophobic Poor wetting	Care while pouring
Polyether	Most impressions	Accurate Short setting time Stable	Very stiff when set Short working time	Care with Undercuts

1.8.1 Conventional and Digital Impression/Digital scanning

Conventional impressions taken in metallic or plastic stock trays are daily procedures carried out in dental practices and it was the only available technique for transferring the details of prepared teeth from the patient's oral cavity to the laboratory (Hamalian et al., 2011, Gjelvold et al., 2015). Although, conventional impressions are widely used, and are the preferred technique for the majority of practitioners (Henkel, 2007), complications are commonly observed and reported such as improper impression tray selection, improper soft tissue management, distortion of the impression material during dis-infection and/or pouring of the impression (Christensen, 2008, Beuer et al., 2008c, Touchstone et al., 2010).

Previously, metallic trays were commonly used for impressions of tooth preparations of one or more units, as they benefited from being rigid, thus providing the stability required for the impression material. However, difficulty was experienced in removal of the tray adhesive and this posed a problem in relation to cross infection control. As such plastic trays are now more commonly used as they are disposable and eliminates potential cross infection issues. Plastic trays do ,however, suffer from being flexible (lack rigidity), which makes it mandatory to use rigid impression materials to ensure the stability needed (Ceyhan et al., 2003, Christensen, 2008, Bensel et al., 2013).

A digital impression technique using intra oral scanners was introduced for transferring the information from the patient's oral cavity to the laboratory using the digital technology, and is described in detail in section 1.6.2.

1.8.2 Cross infection control in relation to impressions

Disinfecting dental impressions is an important procedure to carry out prior to sending them to the laboratory to eliminate cross infection (Wassell et al., 2002b). As dental impressions can be a source of bacterial contamination, education regarding impression disinfection is important to the dentist, dental nurse and dental technician (Almortadi and Chadwick, 2010).

Disinfecting conventional impressions is achieved using liquid solutions which can lead to an irreversible distortion of the impression, especially if immersed for a long time. This will affect the final restoration fit (Adabo et al., 1999, Taylor et al., 2002, Hiraguchi et al., 2012). To prevent or minimise any distortion of the impression material, the manufacturer's recommendations regarding the concentration of the disinfecting solution and immersion time should be followed. Spray disinfectants can be used as these have less effect on the dimensional stability of the impression material (Suprono et al., 2012).

Whilst there is no risk in transferring contaminated material to the laboratory when using a digital impression, there is a risk of cross infection between patients and dentist when using the intra-oral scanner. To address this some companies recommend that the camera head is either covered by a disposable sleeve or removable sterilisable plastic sleeve and the head of the camera then wiped with commercially available disinfectant or immersed in a disinfectant chemical. Digital impressions also eliminate the distortions that can happen to conventional impressions as a result of the disinfection procedure (Glassman, 2009).

1.8.3 Models

The dental models not only aid the dentist and laboratory technician in studying the dental case carefully and in detail, so helping in treatment planning, but they are also essential in the production of the indirect restoration. Most dental models are produced using gypsum products, for example type IV gypsum (Kim et al., 2015).

Dental models can therefore be divided into three types, depending on the usage:

1. **Study model** (cast), used for treatment planning purposes.

2. **Working cast**, used for construction of dental restorations.

3. **Refractory model**, used with metal framework wax-up and for certain all ceramic restorations (Bonsor and Pearson, 2013).

It has been recommended that the dental technician waits between 24 to 48 hours before the stone model is handled for prosthetic work, this is because the dental stone is considered unstable during the setting period (Silva et al., 2012). In addition to being unstable, high rates of delayed setting expansion have been reported with dental stone (Heshmati et al., 2002).

To achieve a successful restoration it requires optimal internal and marginal cement gaps (Soriani et al., 2007). The cement gap (internal and marginal) on conventional stone models is created by using die spacer paint (Lee and Ibbetson, 2000); the number of die spacer coats applied on the stone die will determine the cement gap size. Although it can be argued that increasing the cement thickness might lead to a weak bond between the restoration and abutment tooth, it has been shown that up to 16 coats of die relief does not affect the retention of the cemented restoration (Passon et al., 1992).

To compensate for the problems associated with conventional stone models, a new technology has been used to produce stereolithographic models (SLA or SL; also known as optical fabrication, photo-solidification, solid free-form fabrication, solid imaging and resin printing) using a process known as rapid prototyping which is described in detail in the next section.

1.8.4 Rapid prototyping

Rapid prototyping is the process by which software and hardware work together to produce a customized 3D model from 3D digital data (Beguma and Chhedat, 2014). The 3D digital data is collected using 3D scanners or 3D radiographs such as computerized tomography (Zein et al., 2002).

Rapid prototyping is widely used in many industries such as transportation, energy, consumer goods, education and in the healthcare sector for medical models, surgical guides, hearing aids, implantable devices and highly complicated models in dentistry and medicine (Nayar et al., 2015). A 3D model will help the medical and dental practitioners during the treatment planning by reproducing the problem as a model in a natural fashion.

Two techniques are available to produce the 3D models, namely subtractive or additive techniques (Nayar et al., 2015).

The **subtractive** technique uses a full block of the required material and cutting tools to shape the block into the desired model shape in true CAD CAM fashion (Torabi et al., 2015a). This technique has some limitations, for example, the materials used should be strong, hard and sterilisable, but with the available materials, it is difficult to obtain high quality models. A second limitation lies with the milling machines which have limited and restricted motion, and as such some complex shapes or difficult angles cannot be milled, limiting their use for replicating more basic shapes. As with all new technology advancement (electrical discharge machining, electromechanical machining, electron beam machining, photochemical machining and ultrasonic machining), this technique has become faster and is able to achieve higher degrees of sophistication, but not to the degree that the additive technique can achieve (van Noort, 2012).

The **additive** technique, is defined by the American society for testing and materials as 'The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies'. Additive techniques have an advantage over subtractive techniques because they can fabricate models with much more complex and difficult details (undercuts, voids, and complex geometries) such as sinuses and canals (blood and nerves) (Liu et al., 2006).

1.8.5 Stereolithography (SLA)

An SLA model is produced as a result of a scanned or designed object in a 3D scanner or software. The 3D digital model created is sectioned virtually into thin layers (the more layers the better resolution) and the data is then transferred as a STL file to the 3D printer. The printer usually consists of a laser and a vat of liquid resin on a platform; the laser is used to cure the resin creating the first layer of the model, followed by movement of the platform allowing the laser to scan a new layer of resin on top of the first layer, and so on. Once the model is fully built-up it is rinsed of any access un-cured resin and placed in an ultraviolet oven to be thoroughly cured (van Noort, 2012). SLA models constructed in this manner are used for surgical planning and surgical reconstructing cases (Winder and Bibb, 2005).

1.8.6 Dental application of rapid prototyping

Rapid prototyping is used in many specialities in dentistry not only for surgical planning but it can also be used to produce study models and working models for **prosthodontic** and **implant** restorations (Lal et al., 2006, Papaspyridakos and Lal, 2008) and **orthodontics** to produce orthodontic brackets and aligners (Chan et al., 2004a, Wu et al., 2008). The models help in reducing the clinical working time due to accurate treatment planning (Winder and Bibb, 2005).

1.9 Cements

All indirect restorations are fixed to the teeth using dental luting cements. Choosing the correct cement is as important as all the other stages in the provision of indirect restorations, because this will determine the long-term success of the restoration (Pameijer, 2012). Over the last century and a half a large number of luting cements have been used and some are listed in Table 1.11.

Table 1.11 A timeline of the development of dental luting cements

Cement	Year
Zinc phosphate	1870s
Silicate cement	1940s
Polycarboxylate	1972
Composite resin cement	1975
Glass ionomer cement	1976
Resin-cement	1986
Resin-modified glass ionomer cement	1995
Self-etching and adhesive resin cements	2000s

1.9.1 Ideal properties of a luting cement

The ideal dental luting cements should meet clinical and physical properties both during mixing and cementation (Rosenstiel et al., 1998, Rickman and Satterthwaite, 2010, Pameijer, 2012). The properties include:

1. Biocompatibility with the teeth and surrounding oral tissue.

2. Adhesion and bonding to both the restoration and the tooth structure.

3. It should have sufficient resistance and retention strength against all forces.

4. Low viscosity to ensure flow of the cement into all fine details and to allow full seating of the restoration.

5. Have perfect marginal adaptation to prevent leakage.

6. The material should be available in different shades (when used to cement ceramic or composite indirect restorations).

7. Easy to handle, sufficient working time and easy to clean.

8. Not soluble.

9. Not imbibe to water.

1.9.2 Classification of dental cements

There are different types of luting cements available on the market (Table 1.12) which can be classified into either conventional or contemporary cements with each type having its usage and recommendations (Rickman and Satterthwaite, 2010, Sümer and Değer, 2011, Pameijer, 2012, Mante et al., 2013).

Table 1.12 Cement classification, commercial names, use and their recommendation

Material	Classification	Use	Recommendation	
DeTrey Zinc Phosphate	Zinc Phosphate	Metal based restorations	Mechanical retention	Conventional
Poly-F Plus Zinc Polycarboxylate	Polycarboxylate	Metal based restorations	Mechanical retention	
Ketac Cem, Fuji cements	Conventional GIC	Metal based restorations	Moisture control	
Rely X Luting, Fuji PLUS, Fuji CEM	Resin Modified GIC	Metal based restorations and Ceramic based restorations	Mechanical retention	Contemporary
Variolink, Calibra, Metabond RelyX Arc	Composite Resins	Dentine bonded crowns and conventional restorations	Mechanical and chemical retention	
RelyX Unicem	Self-adhesive resin cement	All types of restoration except veneers	Mechanical and chemical retention	

A study in 2003, showed that using resin cements led to higher (double) retention on the indirect dental restoration when compared with zinc phosphate and conventional glass ionomer cement using different tooth preparation taper(Figure 1.11) (Zidan and Ferguson, 2003).

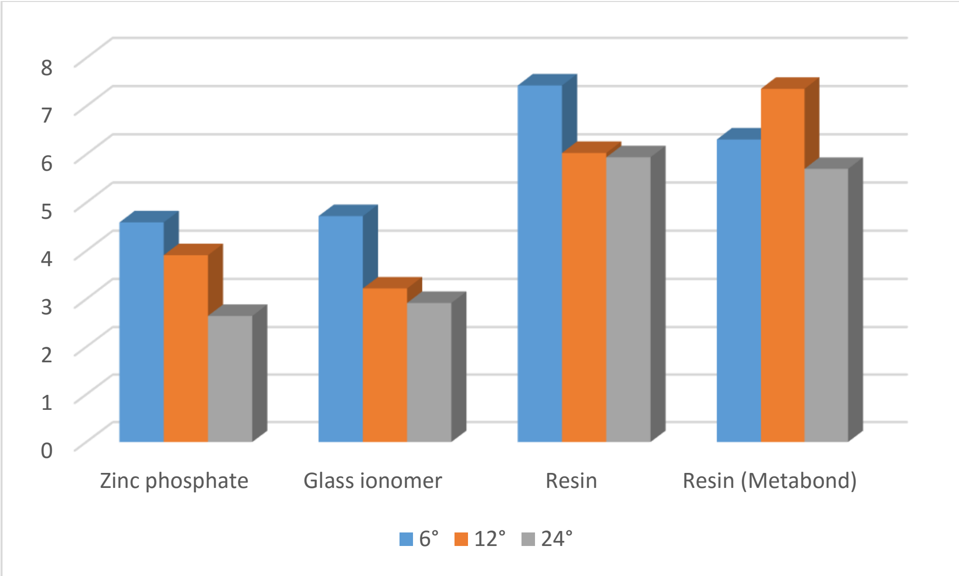


Figure 1.11 Comparisons between mean retentive strength of different degree of taper within each luting agent tested (Zidan and Ferguson, 2003)

1.10 Literature review conclusion and overall aim

The foregoing has reviewed the literature, in relation to different dental materials (metal and ceramics) and their use for fabricating indirect dental restorations with a particular emphasis on dental CAD CAM and digital work flow for the production of zirconia based restorations. There is clearly a rapid increase in interest, research and clinical usage of CAD CAM and digital technology in dentistry and is therefore likely to dominate restorative dentistry in the future. As such, this provided the inspiration for this thesis.

As the survival and longevity of any indirect dental restoration depends on its fit, strength and its appearance, the overall aims of the subsequent studies in this thesis were to investigate the accuracy of **fit** of indirect zirconia based dental restorations produced using dental CAD CAM with differing variables including cementation seating force, differing thicknesses of zirconia and span length, effect of veneering ceramic placement and whether made from a digital or conventional impression. In addition the **strength** (the ability to resist fracture by a force) of bridges made with different thicknesses of zirconia and whether veneered with ceramic or not were investigated. In relation to the **appearance** and fit of zirconia based restorations an audit was also carried out which aimed to measure the dental team and patients' satisfaction with all ceramic zirconia based dental restorations provided for patients at Dundee Dental Hospital and School in addition to an economic evaluation. Each individual aspect is the subject of the subsequent six chapters, each containing the specific aims of the study and discussion of the outcomes.

1.11 Sample size calculation

The sample size for each of the subsequent five laboratory studies was calculated using the on-line calculator: http://www.surveysystem.com/sscalc.htm

The population size was set to 2000 as this could represent the number of people that might require indirect dental restorations within a year within an average dental hospital. With a confidence level of 95 % and a marginal error of 25 %, the results showed that 15 bridges could represent the population. This number is also consistent with previously published work in this field (Khng, 2013). As such in all the laboratory studies in this thesis 15 bridges were produced for each type of zirconia based indirect dental restorations investigated.

Chapter 2

Laboratory study 1

Force applied by dentists during cementation of all zirconia three unit bridges and the impact on seating

Laboratory study 1

Force applied by dentists during cementation of all zirconia three unit bridges and the impact on seating

2.1 Introduction

Cementing an indirect dental restoration is the final step after finishing all the clinical and laboratory stages, and it is considered to be an equally important stage that can affect the longevity of the restoration (Behr et al., 2008). For patients a successful cemented restoration is one that fits perfectly, never de-cements, and does not cause any pain or discomfort. In addition to this the dentist is also concerned with a perfect marginal fit so that no micro-leakage and/or secondary caries occurs (Mustafa et al., 2010). To achieve these goals, after fabricating the indirect dental restoration, the choice of an appropriate luting cement and cementation technique are very important (Wassell et al., 2002a).

The luting cement chosen fills the interface between the fit surface of the restoration and the prepared tooth surface and, in some instances, additionally provides a bond between the two (Rosenstiel et al., 1998). Apart from the luting cement type selected and cementation technique used the force applied by the practitioner might also have an effect on the accurate seating of the indirect dental restoration to achieve the fit ideals described above. In the literature there is no clear recommendation as to the force required to achieve the best seat and hence fit of a restoration. Only two studies have measured the force applied by dentists, both of which were carried out on single unit crowns, and did not study the impact that the applied force had on the fit of the restoration (Black and Amoore, 1993, Mustafa et al., 2010).

2.2 Aims and objectives

The aims of this study were to compare the force applied by ten different dentists and by the same dentists at different time intervals during the cementation of all zirconia bridges manufactured by Computer Aided Design Computer Aided Manufacturing (CAD CAM) and to investigate the impact that this has on the seating and fit of the cemented bridges.

2.3 Material and Methods

Tooth preparation

Two plastic teeth (Frasaco GmbH, Germany) were mounted in Frasaco jaws (standard working model A-3), one first pre-molar (tooth 24) and one first molar (tooth 26), were prepared for a three unit fixed-fixed all zirconia bridge to replace the second pre-molar tooth (tooth 25) (Figure 2.1 A). Each tooth was prepared in the laboratory with a high speed hand piece and new chamfer crown preparation tapered diamond bur (Komet dental, Code number 856-314-016) with water coolant to a predetermined standard: deep chamfer finish-line 1.0 - 1.5 mm around the entire circumference of the tooth preparation, 10° - 12° total occlusal convergence angle (taper) and 1.5 - 2.0 mm occlusal reduction (Byrne, 1992, Chan et al., 2004b, Beuer et al., 2008a, Beuer et al., 2008b, Beuer et al., 2009b, Comlekoglu et al., 2009).

Quality control

Photographs were used to measure the finish-lines (Figure 2.1 B) and total occlusal convergence angles (Figure 2.1 C) of the plastic teeth to confirm that the tooth preparations met the predetermined standard. A Digital Single Lens Reflector camera (DSLR, Nikon D7000) with macro lens (Sigma 105 mm f/2.8 EX DG) and ring flash (Sigma MACRO EM-140 DG) was used to photograph the prepared teeth from 9 different perspectives (Mesial, distal, buccal, lingual, mesio-buccal, disto-buccal, mesio-lingual, disto-lingual and occlusal); the first eight were used to measure the total occlusal convergence angle, and the final occlusal image was used to measure the depth of the cervical chamfer at 12 equally spaced positions around the circumference of the tooth. The images were reproduced at 1:1 ratio. Images were imported into ImageJ (Public domain Java image processing program) to analyse the finish line and axial wall angulations. The mean total occlusal convergence angle for tooth 24 was 11.5° (min 11.1° – max 11.9°) and for tooth 26 was 11.5° (min 11.2°- max 11.7°), the mean chamfer depth around tooth 24 was 1.2 mm (min 1 mm – max 1.3 mm, SD ± 0.1) and tooth 26 was 1.2 mm (min 1 mm – max 1.4 mm, SD ± 0.1).

Figure 2.1 A Prepared teeth (UL4 and UL6) for three unit all zirconia bridges.

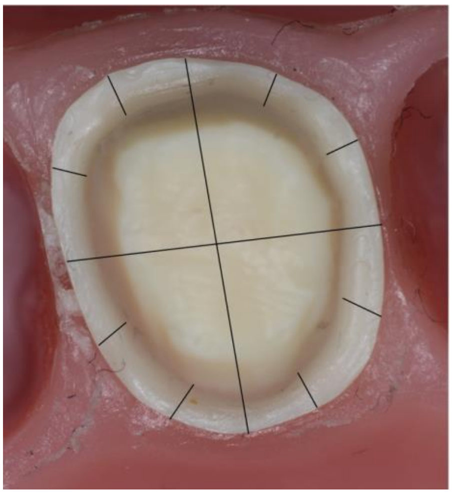


Figure 2.1 B Occlusal image showing measurement of the chamfer finish-line.

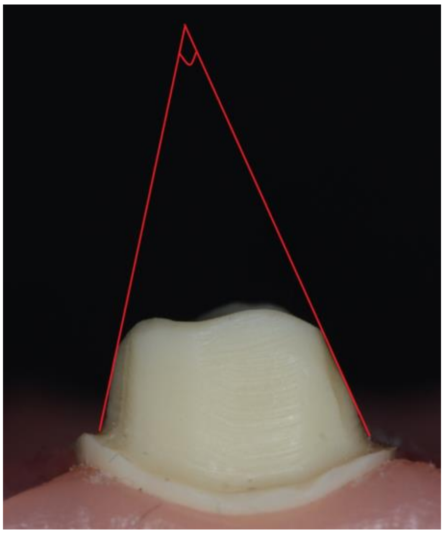


Figure 2.1 C Buccal image showing measurement of the total occlusal convergence angle.

Digital Impression, SLA model and all zirconia bridges manufacture

Once the ideal tooth preparations were achieved and confirmed through the quality control process, the prepared teeth on the original model were scanned with the Lava™ Chairside Oral Scanner (Lava™ C.O.S, 3M ESPE, Seefeld, Germany) according to the manufacturer's instructions to produce ten identical Stereolithography models (SLA models, In'Tech Industries, Inc. USA). This process also allowed subsequent manufacture of ten identical three unit fixed-fixed all zirconia bridges using a five axis CAM milling machine (Lava™ CNC 500 Milling System, 3M ESPE) and dry milling process.

Digital scanning of tooth preparations

The Lava COS scanner was used in exactly the same way as it would be used for a patient, with the prepared Frasaco plastic teeth and jaws mounted in a phantom head (Figure 2.2). The teeth were lightly and evenly sprayed with contrast "patterning powder" prior to scanning as recommended by the manufacturer (3M ESPE; composition: titanium dioxide, amorphous silica, aluminium hydroxide and synthetic amorphous silica).

Following the new case selection on the Lava™ C.O.S and completion of patient identifier data (see flow diagram, Figure 2.3 A), the scanning process was started by selecting the "scan now" icon which led to the scanning home screen page (Figure 2.3 B). In this screen the arch with the preparations was selected (green arrow Figure 2.3 B) and the scan of the abutment teeth and adjacent teeth was completed; only a quadrant scan was captured (Figure 2.3 C). It was ensured that the scan of the abutment teeth was 100.0 % perfect (no missing data highlighted on the scan) and the scan of the adjacent teeth were no less than 80.0 % perfect (missing data highlighted in black on the scan). Once a satisfactory scan was obtained the scan was accepted and the prepared teeth were assigned their correct tooth notation (Figure 2.3 D). The scan of each abutment tooth preparation was then carefully checked to ensure all margins could be marked (Figure 2.3 E). Once satisfied the scans were accepted ✓ .

Whilst the occlusion was not of particular interest in the bridges to be tested, the system required an opposing arch scan to process the work, and In order to minimise the effect of occlusal morphology upon the applied seating force of the subjects the opposing arch was scanned by selecting the lower arch icon (Figure 2.3 B, red arrow), the occlusion was then recorded by selecting the appropriate icon (Figure 2.3 B, blue arrow). This allowed virtual articulation of the models (Figure 2.3 F) and the development of a standard occlusal surface to avoid the potential effect.

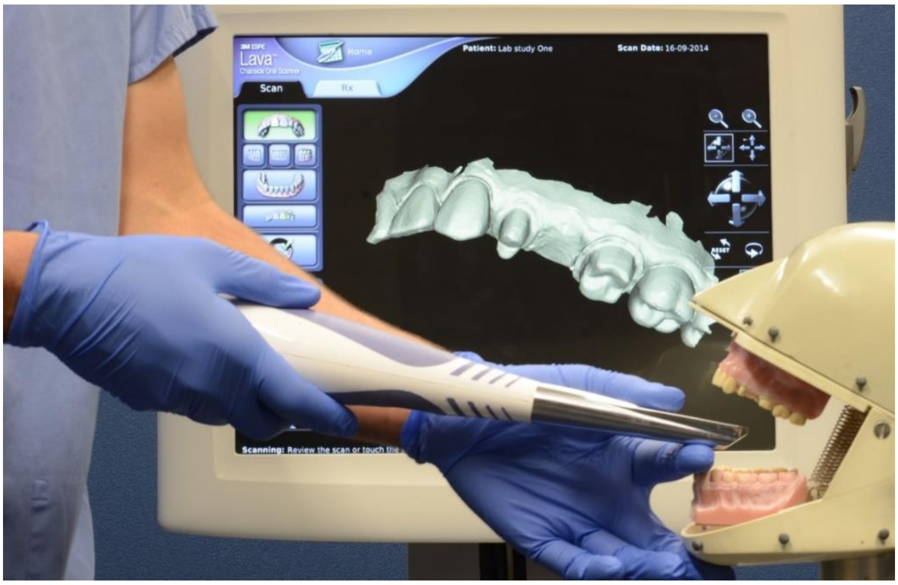
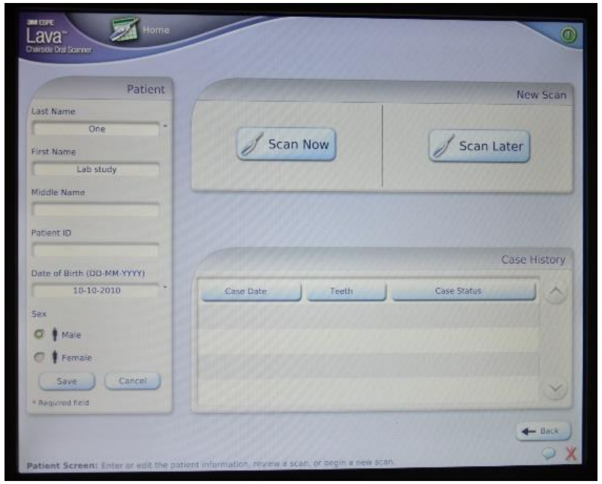


Figure 2.2 Scanning set (Phantom head and Lava C.O.S)

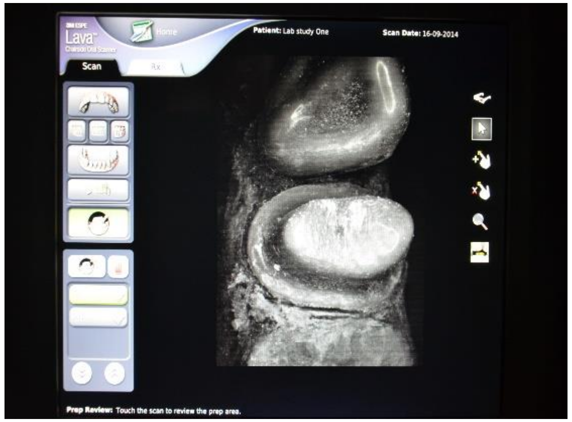


A. Patient identification data

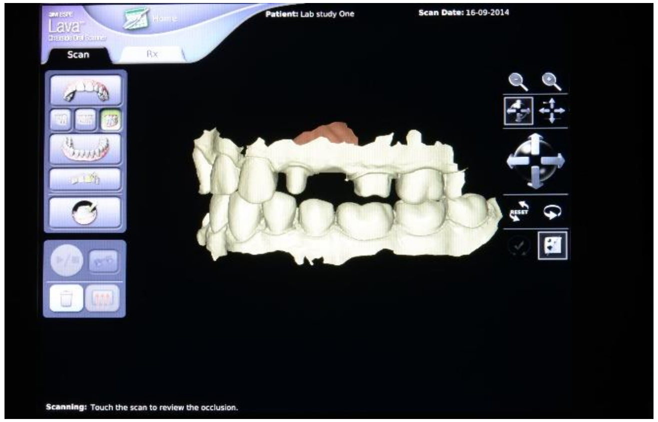
B. Scanning home screen

C. Digital image of scanned prepared

D. Assigning tooth notation



E. Checking abutment scans



F. Recording the opposing teeth and occlusion

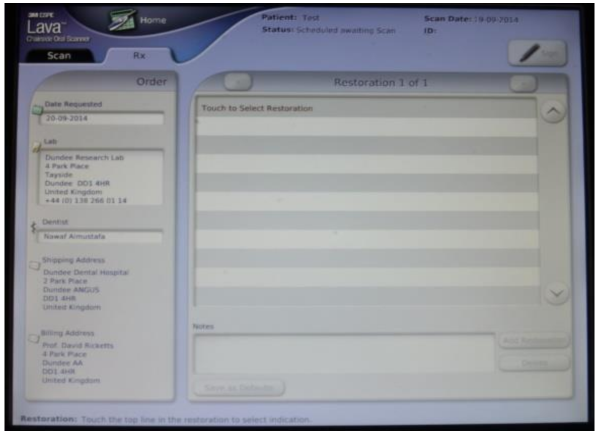
Figure 2.3 Digital scanning of tooth preparation

Finally the prescription order (Figure 2.4 A) was completed by selecting restoration type “Bridge” (Figure 2.4 B), teeth “24 and 26” (Figure 2.4 C), material “All ceramic” (Figure 2.4 D), brand “Lava from 3M ESPE” (Figure 2.4 E) and essential order information (Figure 2.4 F).

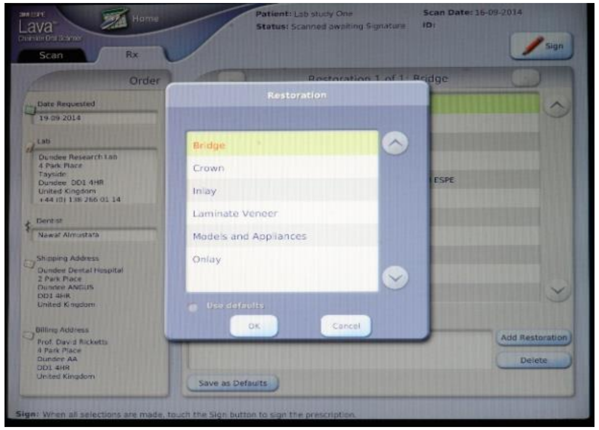
The prescription was then processed through the onsite laboratory using the “3M Connection Centre” program.

SLA models ordering

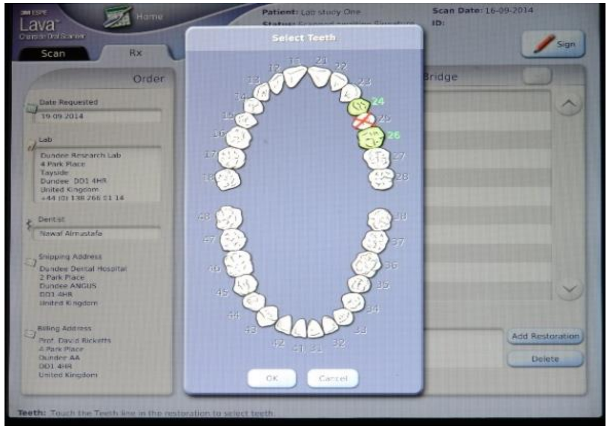
When the case data was downloaded in the laboratory, the “set bite plane” screen was opened to allow virtual articulation of the virtual models and to orientate the articulated models appropriately on the screen. The “Die cut” screen was then selected and the prepared teeth were sectioned on the virtual model. The “Mark Margins” screen was then opened and the finish line was marked on the prepared teeth. After reviewing the case the order was sent to “3M laboratories” to check the models before they sent the data to “In’Tech Industries, Inc. USA” to produce the SLA models (articulated sectioned model and check model (un-sectioned model of the prepared teeth)). Stereolithography is an additive manufacturing process which employs a vat of liquid ultraviolet curable photopolymer "resin" and an ultraviolet laser to build up models one layer at a time. Ten articulated models (sectioned) and ten check models (un-sectioned) were received, the ten check models (un-sectioned) were used for this study.



A. Prescription order form

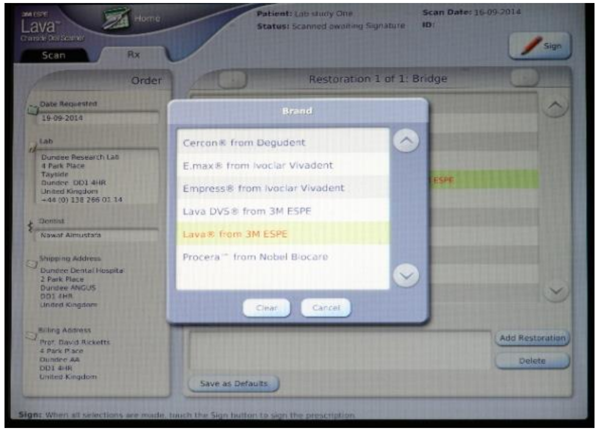


B. Choosing the type of restoration

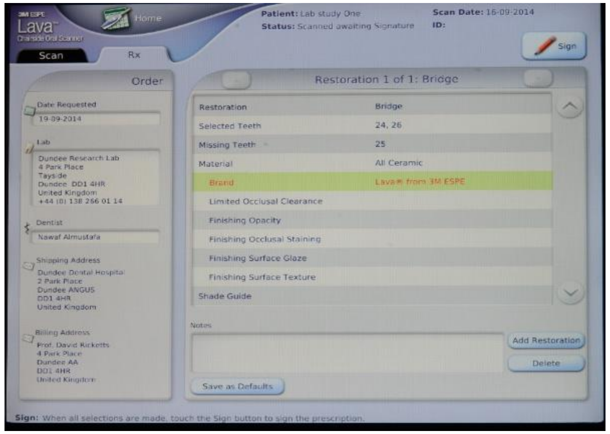


C. Teeth selection (Prepared and missing)

D. Choosing the type of material



E. Choosing the brand of material



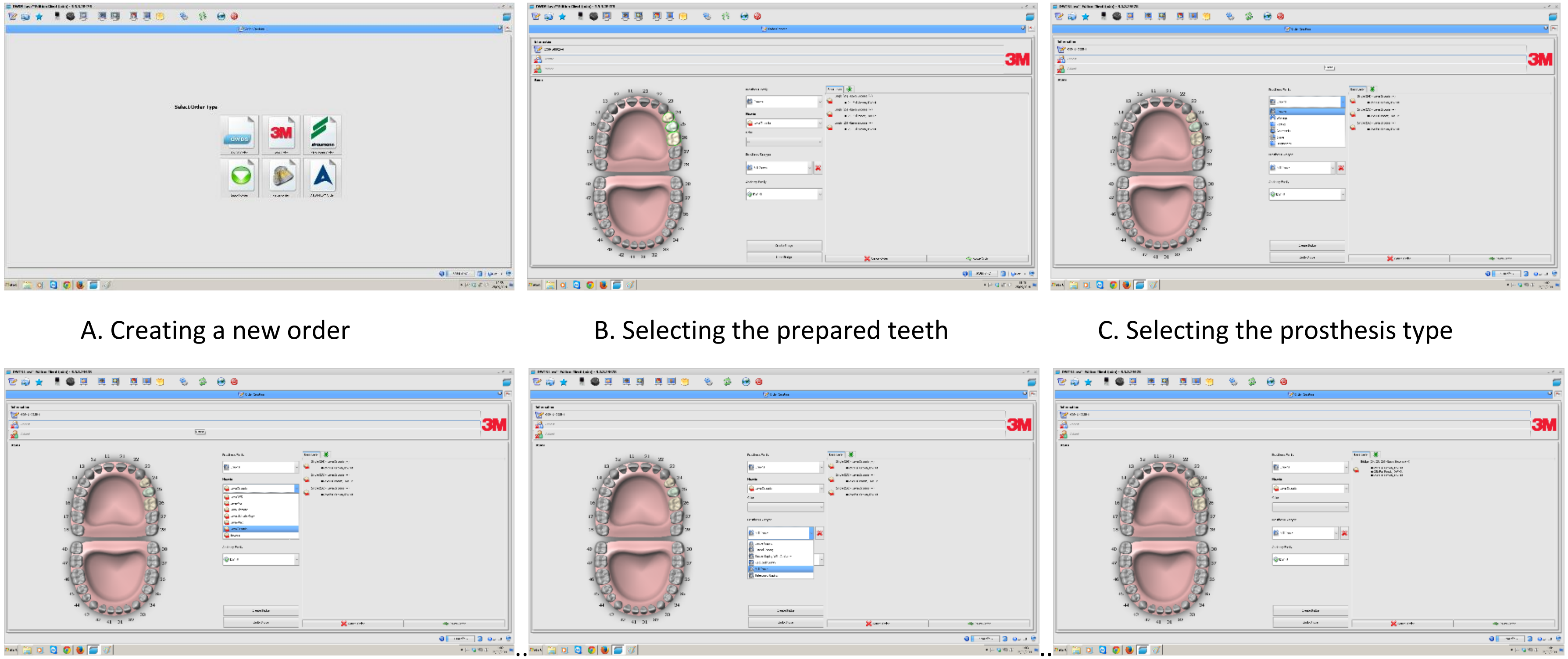
F. Filled Prescrption and ready to sign

Figure 2.4 Filling the order form for the bridge (prescription)

Bridge designing

A new order or prescription should be created for each new zirconia bridge. Lava Design Client software by Dental Wings Operating System (DWOS) was used to design the zirconia bridges from the intra-oral digital scan data. The first stage of creating the order was to initially identify the type of restoration required. For this, under the order creation icon the 3M Lava order icon was selected (Figure 2.5 A). The prepared teeth were then individually selected on the dental diagram (UL4 and UL6) (Figure 2.5 B). For each abutment tooth under the "Prosthesis family" drop down box the "Crowns" item was selected (Figure 2.5 C). Under the "Material" drop box "Lava zirconia" was selected (Figure 2.5 D), and under the "Prosthesis sub type" the item "full crown" was chosen (Figure 2.5 E). For the pontic tooth UL5 was selected from the dental diagram, from the "Prosthetic family" drop down box "Pontics" was chosen, from the "Material" drop down box "Lava zirconia" was selected and from "Prosthetic sub type" drop down box "Full pontics" was chosen. The three teeth were then selected from the dental diagram and the "Create bridge" icon chosen, this allowed the software to connect all the components and finalize the bridge order (Figure 2.5 F).

Once the type of bridge required had been entered, the next stage of the process was to relate the design components of the bridge to the scanned data (virtual model (Figure 2.5 G)). On the virtual model the preparation margins (finish-line) were then identified using the software "Automatic detection of the margin" and adjusted manually with the cursor as necessary (Figure 2.5 H). The axis of insertion was then chosen to allow the software to calculate this for both abutment teeth (Figure 2.5 I). After accepting the axis of insertion the bridge design was completed in the CAD station page (Figure 2.5 J). In this page the cusps, contact points and connectors were adjusted and the final bridge was checked and accepted (Figure 2.5 K). The die-spacer is automatically calculated by the CAD software (die spacer 0.095mm extra vertical (occlusal), 0.075 mm extra horizontal (buccal, mesial, distal and lingual), and 0.025 mm on the margin) and minimum coping thickness 0.5 mm. The bridge data was then routed to Lava Design Software 7 (Figure 2.5 L) to assign the virtual bridge to the zirconia block to be used in the milling machine.



A. Creating a new order

B. Selecting the prepared teeth

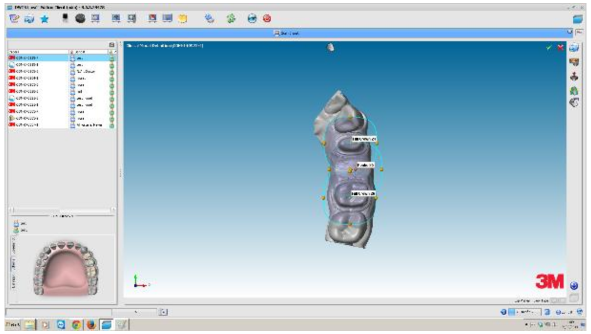
C. Selecting the prosthesis type

D. Selecting the material

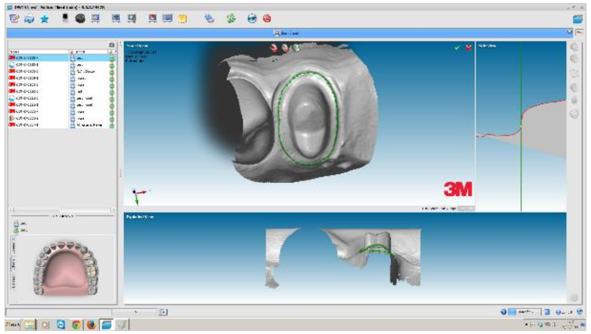
E. Selecting prosthesis sub type

F. Creating the FPD

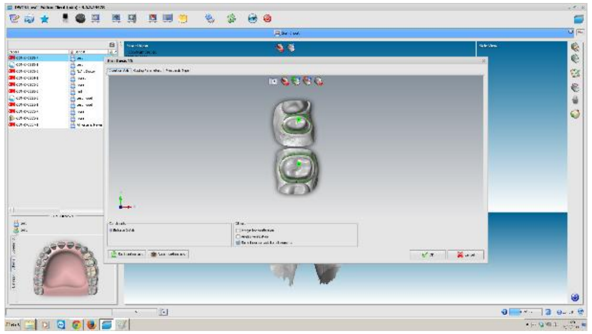
Figure 2.5 Lava Design Client software by Dental Wings



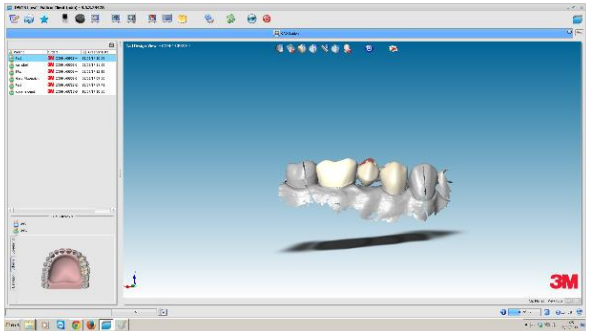
G. Assigning the teeth on the model



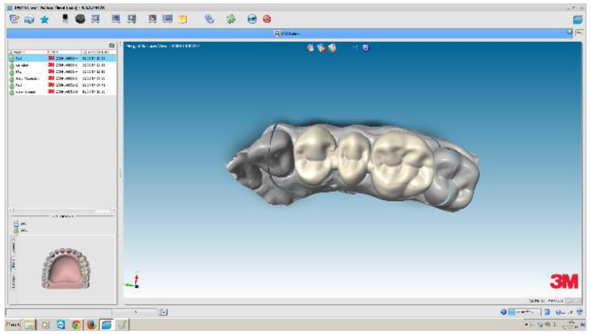
H. Assigning the finish-line



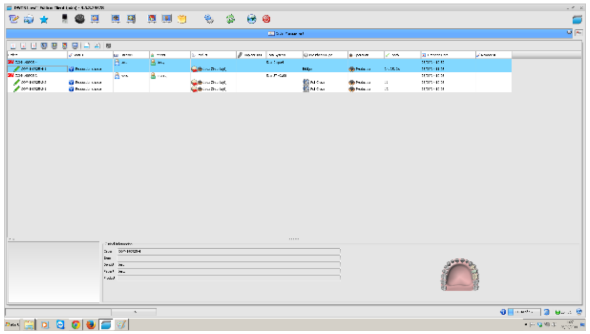
I. Axis of insertion for both abutment



J. FPD designing (CAD station)



K. Finished FPD



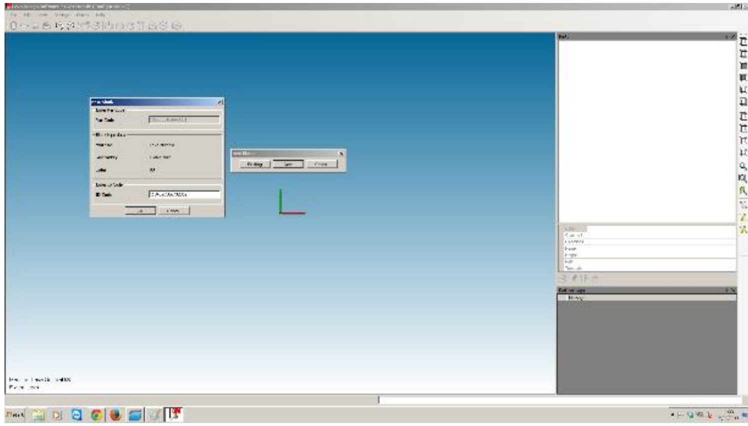
L. Retrieving design file to CAM system

Figure 2.5 Lava Design Client software by Dental Wings

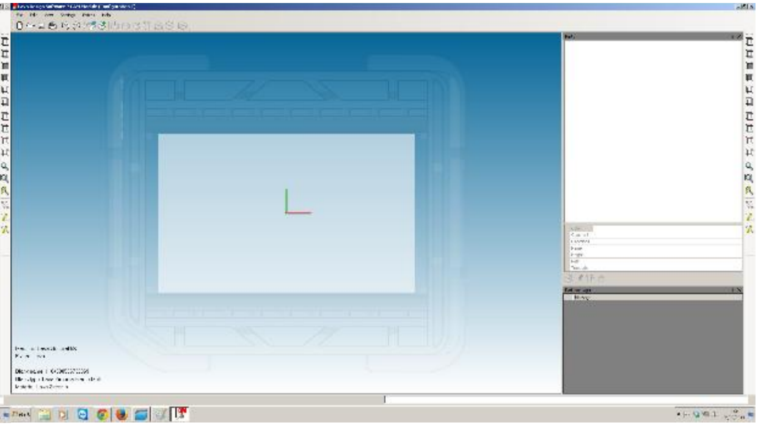
Bridge final order step

In the software the "Load blank" icon was selected to add a new zirconia block or to choose an existing block (Figure 2.6 A). The bar code for each unique zirconia block was scanned (Figure 2.6 B) allowing the system to accurately compensate for the amount of contraction (20.0 – 25.0 %) on sintering for that individual zirconia block. The uploaded virtual bridge was then allocated to the chosen zirconia block and connectors were added to the design to hold the bridges in place during the milling process. Using the same process a further three bridges were added into a Multi Block (Figure 2.6 C & D). The Lava Design Software 7 then calculated the time required, the burs to be used and the bur pathways for the milling machine (Lava™ CNC 500). This information was then sent to the 5-axis milling machine for manufacture of the semi-sintered all zirconia bridges. Semi-sintered zirconia multi blocks were used to fabricate the all zirconia bridges (3M ESPE, Seefeld, Germany, LOT No. 470281, LOT No. 472678 and LOT No. 472678).

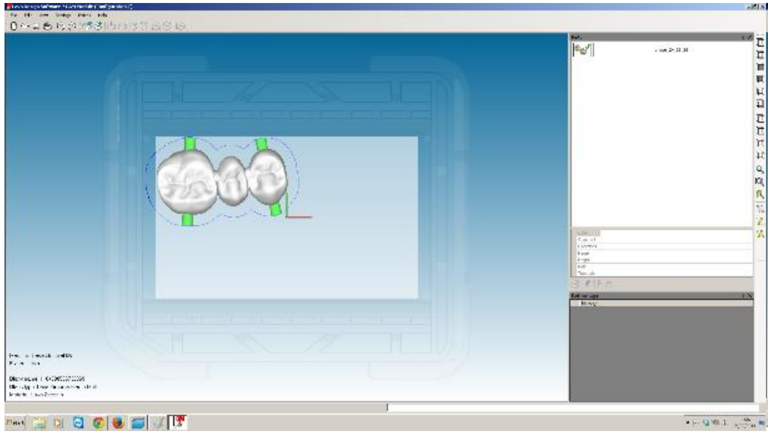
Following milling the semi-sintered all zirconia bridges were removed from the zirconia multi blocks by carefully sectioning through the connectors (sprues) and placed in a custom furnace (Lava™ furnace 200, 3M ESPE, Seefeld, Germany) to fully sinter the all zirconia bridges at 1500°C for 4 hours 48 minutes (LAVA 1500, Non-shaded). Ten identical all zirconia bridges were thus produced and were used with the ten identical SLA check models for this study.



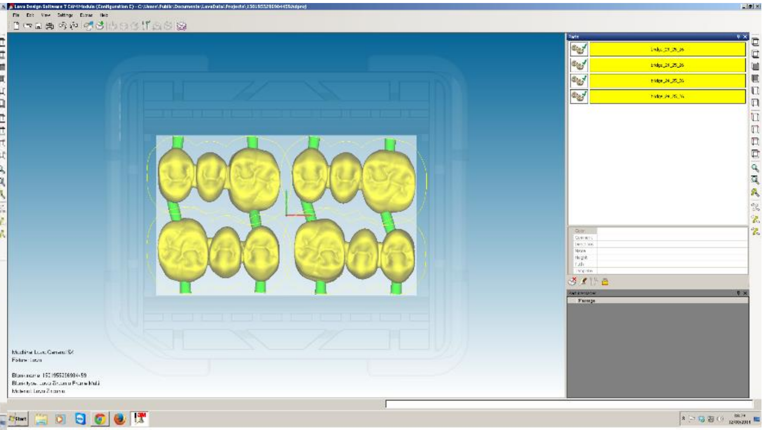
A. Scanning the bar code



B. Multi zirconia block



C. Virtually loading the bridge



D. Loading four bridges in the block

Figure 2.6. Loading the virtual bridges to the zirconia blocks

Force applied during cementation procedure

Ten practitioners were recruited for this study and allocated one SLA model and one all zirconia bridge each. All practitioners were qualified dentists: six were consultants in restorative dentistry and four were postgraduate students in restorative dentistry, all having at least five years post graduate experience. RelyX™ Unicem 2 Clicker™ (3M ESPE, Seefeld, Germany, LOT No. 491286) self-adhesive Universal Resin Cement was used as the luting cement. So that repeated cementations of the same bridge could be carried out on different occasions, only the base paste of this material was used to prevent setting of the cement.

For each cementation procedure the internal aspect of the two all zirconia bridge retainers were coated with the base cement and the practitioners were instructed to seat the bridge with the force that they would use clinically to cement a bridge, using two fingers, one over each retainer (as previously determined in a pilot study of ten dentists' cementation technique) for two minutes. To measure the cementation force (Newton), the SLA model was placed on a universal testing machine (Instron®, model 4469) table while the all zirconia bridges were cemented by the dentists. A stop watch was mounted on the Instron machine alongside its control panel force display. A continuous recording video camera captured the force and time for each cementation procedure: cementation force was recorded at 10 second intervals for two minutes.

Each examiner performed the seating procedure six times over a two week period, blind to the cementation force and previous recordings: three times each week on alternate days. After each cementation procedure the base cement was thoroughly cleaned from the fit surface of the bridge and from the prepared teeth by brushing them under running hot water followed by drying with tissue paper. On the final cementation, the base and catalyst pastes were mixed and the bridge immediately cemented permanently, excess cement was removed using a micro-brush, the participants applied the force for two minutes and then the cement was light cured at the bridge margins.

Embedding and sectioning bridges

The cemented bridges on the SLA models were stored dry and after one week the SLA models and the cemented all zirconia bridges were embedded in Orthoresin (self-curing, DENTSPLY, DeguDent Gmbh, Germany, and LOT NO. 13FEB096 (powder), 12AUG045 (liquid)) to ensure that the bridges and resin teeth did not fragment during the sectioning process. Each model was sectioned bucco-lingually and mesio-distally through each retainer using an IsoMet® 5000 Linear precision saw (Buehler®, a division of Illinois Tool Works Inc.) with an IsoMet® diamond wafering blade (178mm x 0.6mm, Buehler®) under water coolant, for subsequent examination under the Scanning Electron Microscope (SEM). Each retainer and abutment tooth were therefore sectioned into 4 segments (Figure 2.7 A).

SEM observation

Sectioned samples were mounted on aluminium studs using double sided carbon tape, then painted with silver conductive paint (conductive pen, MG chemicals). The samples were then examined under the Scanning Electron Microscope (SEM, Philips XL30 FEG SEM) at 150x magnification operating at acceleration voltage of 15 kV (to measure the cement space internally and marginally). The images were viewed on a 19" flat screen using Microscope Control software (Figure 2.7 B). For each bridge (and examiner) there were eight segments (four from the premolar and four from the molar) and each segment had two walls (Table 2.1).

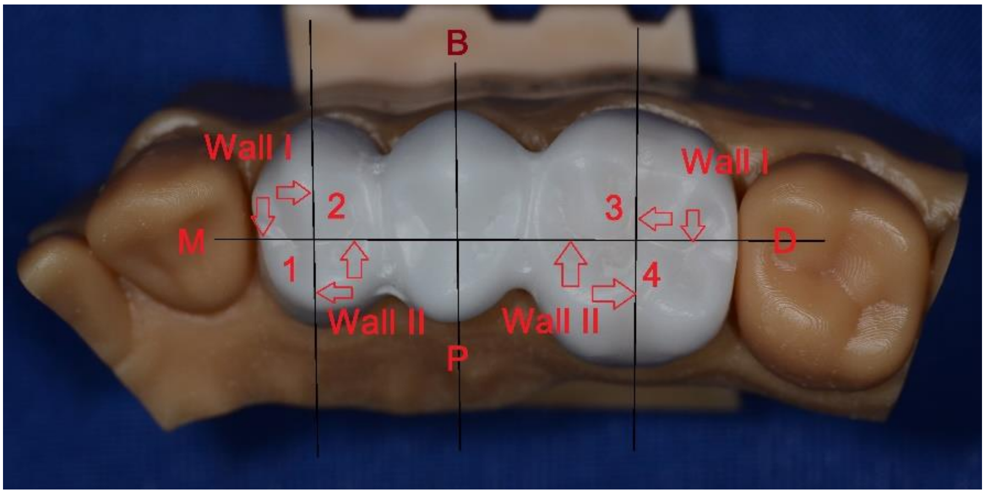


Figure 2.7 A SLA model and bridge section lines

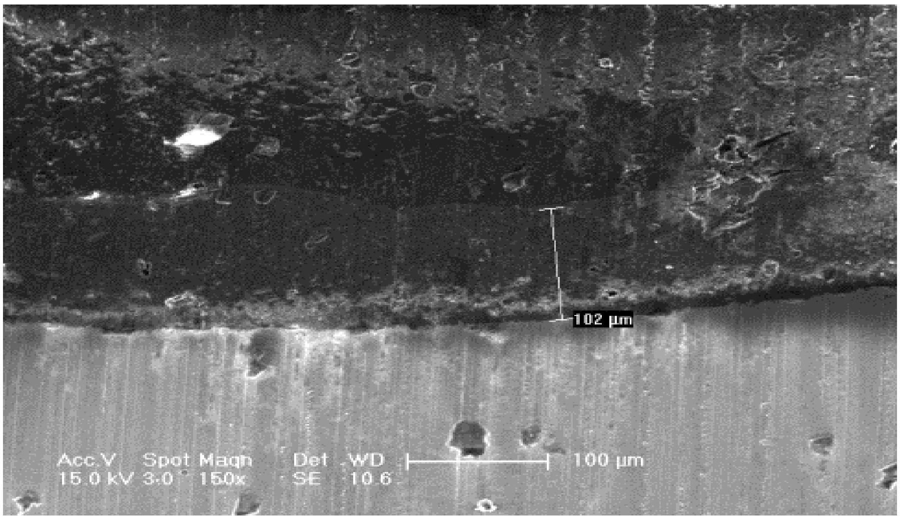


Figure 2.7 B Measurement of internal fit (cement space)

Table 2.1 showing the four segments locations from the three unit all zirconia bridge and the walls related to each segment.

Segment	Wall 1	Wall 2
Segment 1 (Premolar)	Mesio-Distal	Bucco-Palatal
Segment 2 (Premolar)	Bucco-Palatal	Mesio-Distal
Segment 3 (Molar)	Bucco-Palatal	Mesio-Distal
Segment 4 (Molar)	Mesio-Distal	Bucco-Palatal

For each wall, measurements for internal fit were recorded at twenty six randomly selected sites (4 occlusal and 22 axial) and for marginal fit seven measurements were recorded in the region of the horizontal chamfer.

Statistical analysis

For each practitioner the mean force taken at each 10 second interval for the 2 minutes cementation period was calculated for the six cementation procedures. Two way ANOVA with post hoc testing (Bonferroni) were used to assess the force applied by the practitioners during the six different cementation procedures and to determine if there was any significant difference between the cementation procedures for each practitioner and between practitioners. The final cementation force was investigated using a one way ANOVA and post hoc (Bonferroni) test to determine if there were any differences in the forces applied by the practitioners for the whole two minute cementation procedure and at each 10 second interval. The mean internal and marginal fits were assessed for each practitioner using two way

ANOVA and post hoc (Bonferroni) to determine if there was any differences between them (IBM® SPSS® 21). The relationship between the mean internal and mean marginal fits with the final cementation force applied was investigated using the Pearson Correlation co-efficient.

2.4 Results

Force

All six cementation procedures

Analysis of the force applied at every 10 second interval over the two minute cementation procedure for all 10 practitioners on the six separate occasions, showed that the mean force applied was 27.2 N (min 8.0 N, max 88.0 N, SD ± 7.9).

For each practitioner, two way ANOVA showed that there was no statistically significant difference between the cementation forces applied in every 10 seconds over the two minutes in the six cementation procedures ($p = 0.19$). However there was a significant difference in the mean force applied over the six, two minute cementation procedures between the practitioners ($p \leq 0.001$). Post hoc test (Bonferroni) showed that for most paired comparisons between practitioners there was a statistical significant difference in force applied (Table 2.2).

Observation of the cementation force overtime showed that individual practitioners consistently applied higher forces during the first 20 second period. Two way ANOVA showed that in the first 20 second period all ten practitioners applied different cementation forces ($p \leq 0.05$) However, the force applied over the remaining time (100 s) periods was less variable between practitioners with post hoc test

(Bonferroni) showing that the cementation force was only statistically different between two practitioners (2 and 3; $p \leq 0.01$).

Table 2.2 Post hoc comparisons of cementation pressure/ forces between practitioners (*P ≤ 0.05; **P ≤ 0.001; the yellow boxes shows no statistically significant difference)

- Practitioners	1	2	3	4	5	6	7	8	9	10
1		*	**	0.155	1	**	0.062	**	1	**
2			**	*	**	**	**	**	0.024	**
3				**	**	**	**	**	**	**
4					*	**	1	*	0.024	**
5						**	*	**	1	**
6							**	*	**	1
7								*	*	**
8									**	1
9										**
10										

Final cementation

In the last cementation procedure the mean force applied for all ten practitioners over the two minute cementation procedure was 28.2 N (min 13.0 N, max 59.0 N, SD ± 9.5).

One way ANOVA showed statistically significant differences ($p \leq 0.05$) in the cementation force applied by the ten practitioners over the entire two minute procedure. However, post hoc test (Bonferroni) showed there to be a statistically significant difference between practitioners only in the first 10 and last 20 seconds ($p \leq 0.05$). The mean force in the first 10 seconds was 38.3 N (min 20.0 N, max 59.0 N, SD ± 14.6) and thereafter 27.3 N (min 13.0 N, max 52.0 N, SD ± 8.4) (Figure 2.8).

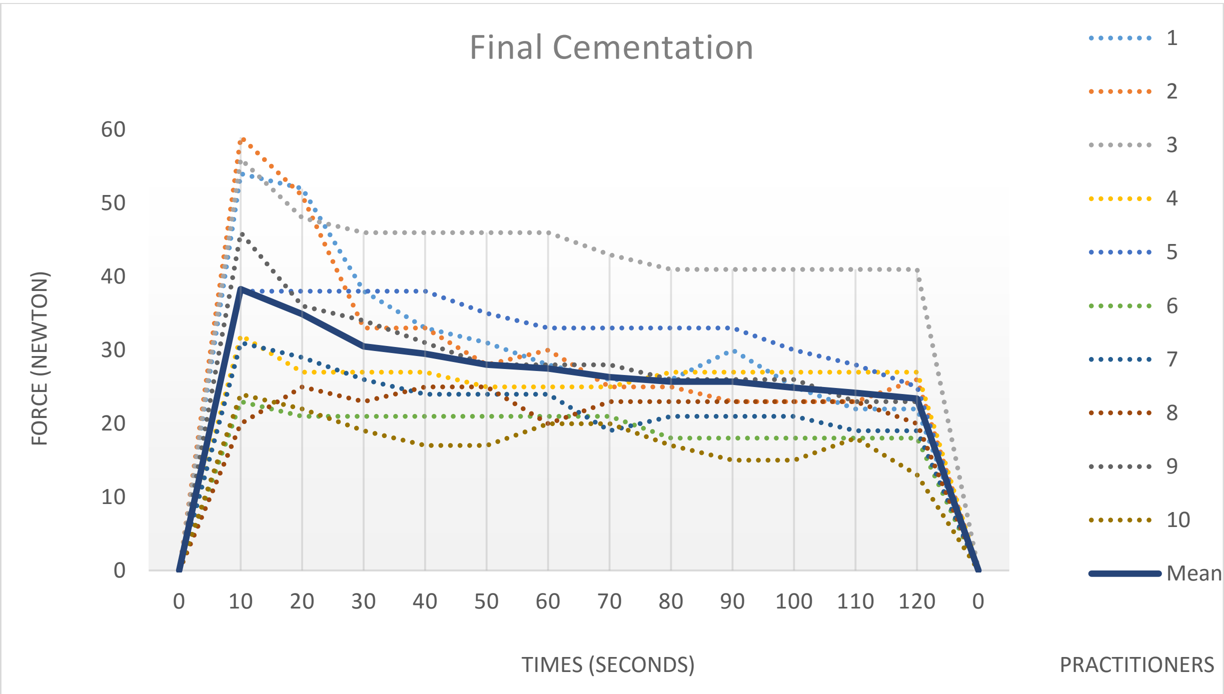


Figure 2.8 Force for each practitioner (dotted lines) and mean force (solid blue line) applied from the final cementation experiment

Internal and marginal fit

Analysis of the readings of internal fit results for both abutment/retainers and all practitioners showed a mean gap of 90.4 µm ± 0.6 (min 79.4 µm, max 106.7 µm). Two way ANOVA showed a statistically significant difference in internal fit between the practitioner's cemented FPDs ($p \leq 0.05$); post hoc (Bonferroni) test showed that the results of practitioner 3 only had significant difference from the other practitioners, where all the other practitioners showed no significant difference in internal fit. Where marginal fit was concerned (mean 28.4 µm ± 0.2, min 24.1 µm and max 31.5 µm) there was no statistically significant difference between the practitioners ($p = 0.714$).

Analysis of the marginal gap of the mesial aspects of the premolar and distal of the molar teeth were examined statistically (two way ANOVA) to check if there was any impact which may arise from a different force being applied by each finger on different abutments, the results showed no significant difference ($p = 0.897$).

Force and fit

Comparison of the mean internal fit and marginal fit with the mean force applied for all participants showed that there was a moderate to strong inverse relationship between force applied and internal fit (Pearson Correlation Coefficient = - 0.69; $P \leq 0.05$) and no statistically significant relationship to marginal fit (Pearson Correlation Coefficient = - 0.28; $P = 0.16$). One examiner stood out in applying a greater force for the duration of the cementation; elimination of this examiner from the analysis resulted in no statistically significant relationship in the cementation force and internal or marginal fit.

2.5 Discussion

The two previous studies that have investigated the cementation force used by dentists in seating indirect restorations have focussed on single unit crowns. These studies have shown that the forces generally applied ranged from 12.0 to 67.0 N (Black and Amoore, 1993, Mustafa et al., 2010). It is possible that when cementing more substantial restorations involving two or more teeth and having a longer span, the dentist could apply different forces, however, this study showed that the forces applied are, in general, comparable, in the order of magnitude of 8.0 to 88.0 N.

The digital files produced by the intraoral scanner (Lava COS) in this study were used to produce multiple, identical SLA models and corresponding bridges. It is important that the models were identical so that any differences in fit was as a result of the dentists' cementation force and not a difference in model dimensions. In 2014 Patzelt et al. conducted a study to compare multiple SLA models created with two intra-oral scanning systems (CEREC AC with Bluecam and the Lava™ C.O.S) with that of milled models also produced from compatible intra-oral scans (produced by iTero, Align Technology, San Jose, California). Using a laboratory reference scanner as a gold standard it was found that the models produced with all three systems were clinically fit for purpose, however the SLA models were more accurate, with the models produced using the Lava™ C.O.S having the highest degree of precision and reproducibility (Patzelt et al., 2014a). These results therefore gave confidence in the use of the Lava™ C.O.S SLA models in this and subsequent studies in this thesis.

In the normal manufacture of SLA models the manufacturer provides articulated models with sectioned dies and un-sectioned (check) models. The sectioned models facilitate the manufacture of restorations by enabling the individual master die to be removed from the arch, so that additions and adjustments of veneering ceramic can be carried out more easily. However, the gap created in the sectioned models allows some movement of the abutment teeth, which could affect the internal and marginal fit when different cementation forces were used, as the dies could move to achieve the optimum fit. As such in the study only the un-sectioned check models were used to avoid the problem.

RelyX Unicem cement was used in this study as the luting cement, as it is the cement recommended by the manufacturer of the CAD CAM system and that used in previous studies hence allowing comparisons to be made (Scotti et al., 2011, Son et al., 2012, Ahrberg et al., 2015). Although Rely X Unicem is a dual cured cement, in the final cementation in this study it was light cured to ensure that the cement had set at the marginal gap, duplicating the clinical procedure. The manufacturer's recommendations for the complete setting time for Rely X Unicem is either 6 minutes for self-cure or up to 3 minutes for light-cure (RelyX™ Unicem Clicker™ 3M ESPE, cementation technique). In the real clinical situation it is very difficult and painful (for patient and dentist) to keep a seating force for more than two minutes continually and Figure 2.8 shows that fatigue probably explains why the seating force gradually decreases with time. Hence, in this study, a two minute seating force and then light cure was considered to realistically represent what happens clinically.

The force application in the clinic is sometimes achieved by the dentists asking patients to bite on a cotton roll placed between the restoration and the opposing teeth to finally seat the restoration (Wassell et al., 2002a, Silvey and Myers, 1977). This could pose a problem in longer span bridges in that an equal and balanced force over each abutment tooth is required and may not be achieved, especially posteriorly in relation to the hinge movement in opening and closing, when asking patients to bite to seat the restoration. It has also been shown that patients can achieve a much greater maximum bite force of 350 to 850 N between posterior teeth (Bates et al., 1975, Gibbs et al., 1986) and 120 to 350 N between anterior teeth (Helkimo et al., 1977, Tortopidis et al., 1998), than was achieved by dentists cementing restorations in this study and previous studies (Black and Amoore, 1993, Mustafa et al., 2010). Not only is maximum bite force influenced by the position in the arch, but there are other different factors that can affect the bite force:

Gender may have an influence on the bite force, studies have shown that males exert a higher maximum bite force compared to females (Helkimo et al., 1977, Shinogaya et al., 2001, Koç et al., 2011).

The maximum bite force is reached at the age of 20 to 40 years, and then starts to decline (Kiliaridis et al., 1993, Bakke, 2006, Palinkas et al., 2010).

Craniofacial variables. Patients with different facial types (short, average and long face) produce different bite forces with the highest force applied by people with short faces, followed by people with average faces and the lowest recorded from people with long faces (Ringqvist, 1973, Kiliaridis et al., 1993, Waltimo et al., 1994, Bonakdarchian et al., 2009).

The number of teeth present plays another role on the strength of the bite force. Patients with a full dentition demonstrate the highest maximum bite force, followed by those with bridges, then removable partial dentures and finally people with complete dentures showed the lowest maximum bite force (Helkimo et al., 1977, Bakke et al., 1990).

Patients with poor periodontal condition may have lower levels of maximum bite force (Williams et al., 1987, Alkan et al., 2006). However, some studies have shown that the effect of periodontal health has a negligible effect (Kleinfelder and Ludwig, 2002, Morita et al., 2003).

Temporo-mandibular disorders that relate to any pain or disturbance to the masticatory system and masticatory muscle pain can limit or lower the maximum bite force of a person (Kogawa et al., 2006, Pizolato et al., 2007).

It is also unknown how sustained the bite force is over time when used to cement restorations. As such the practice of asking patients to use occlusal force to seat restorations should be discouraged due to its uncontrolled nature.

In studies which have investigated the retention of cemented crowns, sustained uniform seating forces have been applied to seat and secure the restorations. The forces used have ranged from 50.0 N to 200.0 N (Proussaefs, 2004, Palacios et al., 2006, Johnson et al., 2009). The duration over which seating force is applied when cementing a dental restoration could also have an impact on the flow of cements, the final cement film thickness, fit and retention of a restoration. The effect of applying a constant seating force of 100.0 N over a five second and three minutes period of time has been investigated when Panavia F was used with and without Clearfil Protect Bond. The prolonged application of constant seating force and the use of a hydrophobic light-cured adhesive (Clearfil Protect Bond) both resulted in improved bond strength of resin blocks cemented on natural teeth (Chieffi et al., 2007).

In two publications that have examined the fit of indirect restorations it has been stated that 50 measurements per restoration are required to fully appreciate the accuracy of fit (Groten et al., 2000, Nawafleh et al., 2013). It has also been recommended that the number of measurements should be related to the sample size: however for most studies if there were around 30 specimens then approximately 20 to 25 measurements per crown or retainer would be acceptable (Nawafleh et al., 2013). Hence in this study readings were recorded at 33 randomly selected sites for each sample wall, (26 internal (4 occlusal and 22 axial) and 7 marginal) making a total of 66 readings for each retainer-abutment interface. The readings for internal fit in this study were greatest occlusally followed by the axial walls, with the marginal fit having the closest adaptation. The actual internal and marginal fit of the restorations, whilst closely reflecting the default die spacer dimensions used when designing the restoration in the CAD software, did increase slightly in all areas: CAD CAM default die spacer = 95.0 µm occlusal, 75.0 µm axial and 25.0 µm marginal compared with actual mean fit of 90.4 µm internal (occlusal and axial combined) and 28.4 µm marginal.

In this study the occlusal and axial internal fit readings were dealt with as one reading separate from the marginal fit. Combination of the two internal surfaces (occlusal and axial) was felt to be acceptable as only 4 occlusal readings were taken when the larger default die spacer was used and the fact that the default die spacer difference on the occlusal and axial walls was so small, namely 20.0 µm.

The results in this experiment (mean internal = 90.4 µm and mean marginal = 28.4 µm) are comparable to the readings from previous studies which have looked at internal and marginal fit of CAD CAM based restorations. For example, in previous studies of all ceramic restorations the internal fit has been found to range from 60.5 µm to 109.5 µm and the marginal fit ranged from 17.0 µm to 132.2 µm (Bindl and Mormann, 2005, Lee et al., 2008, Marcela Herrera et al., 2012, Song et al., 2013). The large range in the results, especially for marginal fit can be explained by a number of factors, firstly the use of different CAD CAM systems (manufacturers) could influence the fit, as each CAD CAM system software has its own default settings when creating the die spacer for internal and marginal gaps (Bindl and Mormann, 2005, Lee et al., 2008, Marcela Herrera et al., 2012, Song et al., 2013). In addition to the CAD CAM system used, the type of restoration, whether all zirconia or zirconia frame work, and the finishing technique used for the latter (free hand build-up of veneering ceramic, pressable ceramic or CAD-on technique) which will include different firing cycles, can affect the restoration fit and hence cement gap (Kunii et al., 2007, Lee et al., 2008, Vigolo and Fonzi, 2008, Romeo et al., 2009, Tao and Han, 2009, Kohorst et al., 2010, Bhowmik and Parkhedkar, 2011, Cho et al., 2012, Euan et al., 2012, Miura et al., 2014, Torabi et al., 2015b). However, this is not the focus of this laboratory study and will be investigated in the second laboratory study. Finally the type of the indirect restoration, whether a single unit crown or bridge with multiple (and variable number) of units might also have an effect on fit (Tinschert et al., 2001b, Bindl and Mormann, 2005, Komine et al., 2005, Reich et al., 2005a, Bindl and Mormann, 2007, Komine et al., 2007, Reich et al., 2008, Stappert et al., 2008, Vigolo and Fonzi, 2008, Att et al., 2009, Beuer et al., 2009a, Beuer et al., 2009d, Dittmer et al., 2009, Gonzalo et al., 2009, Abduo et al., 2010, Lee et al., 2013a, Anunmana et al., 2014), and this will be covered in detail in the third laboratory study.

The bridges made in this study were all zirconia and were made to the expected natural contour of teeth. They were made from the same digital file by the same CAD CAM system (Lava, 3M ESPE), with the aim of minimising any technical errors and to ensure the bridges produced and the models were identical. Such all ceramic restorations are termed in some studies (Lee et al., 2008, Matsuzaki et al., 2015) as a single layer all ceramic restoration or monolithic zirconia, as opposed to a double layer or porcelain layered restoration where a zirconia coping is made and veneered with conventional ceramic. It is possible that by placing the zirconia coping back in the furnace to fire an aesthetic ceramic veneer, some distortion of the coping could occur affecting the fit, this will be discussed in detail in the second laboratory study.

The results from this study have shown that different practitioners exert different forces when cementing three unit bridges, especially in the first 10 seconds of application. However the force exerted by each dentist is repeatedly consistent. Whilst different forces may be applied when seating the bridges there was little or no impact on the internal and marginal fit respectively, with only one main outlier, practitioner 3, who exerted a sustained higher force throughout but having a bridge of similar marginal fit.

It could be argued that the force applied in such an artificial environment as in this study, may be different to that applied intra-orally. But since the examiners used a range of forces with no impact on fit this is unlikely to be a problem clinically.

2.6 Conclusions

Within the limitations of this study, the following conclusion can be drawn:

1. Dentist apply different forces when cementing bridges.

2. Initial force is the highest and it starts to plateau after 30 Sec.

3. In the final cementation experiment the mean forces applied were between 13 N and 59 N, leading to clinically acceptable marginal and internal fit of the final cemented all zirconia three unit bridges.

4. In summary, different seating forces applied to the bridges during cementation do not influence the fit of the restoration.

Chapter 3

Laboratory study 2

The effect of firing cycles and zirconia thickness on the internal and marginal fit of zirconia bridges

Laboratory study 2

The effect of firing cycles and zirconia thickness on the internal and marginal fit of zirconia bridges

3.1 Introduction

Metal ceramic indirect dental restorations were the restoration of choice for many years, mainly due to their long history of use and predictable outcomes (Sundh et al., 2005). Whilst satisfactory aesthetic results can be obtained with metal ceramic crowns, heavier tooth reduction is required to provide sufficient space for the metal coping, opaquing and veneering ceramics. Even when this is carried out, problems can arise in poor translucency and lack of a natural appearance. With the high demand for aesthetic restorations, all ceramic based restorations were introduced and have become widely used in contemporary practice due to the improved aesthetics and strength (Sundh et al., 2005, Manicone et al., 2007) compared to metal ceramic crowns.

The relatively new concept of manufacturing highly precise indirect dental restoration using CAD CAM systems has made it possible to produce restorations from stronger ceramics such as zirconia (Beuer et al., 2008c). Whilst the pre-sintered zirconia blanks used to mill all zirconia (single layer) CAD CAM restorations are white, once they have been milled they can be coloured using dyeing liquid (monochrome dip shading) prior to sintering in the furnace. Such all-zirconia restorations are therefore tooth coloured, but are monochromatic and suffer from a lack of characterisation. Therefore for restorations in the aesthetic zone the zirconia bridges are usually made as much thinner copings and frameworks to allow space for veneering dentine and enamel ceramics (Tuncel et al., 2014). Although, the manufacturer of CAD CAM systems claim that the dental restorations fabricated using their systems are of great internal and marginal fit, some studies have shown that the final restoration fit can be affected due to factors such as the firing cycles and in particular the additional firing cycle required for the veneering ceramic (Cho et al., 2012, Euan et al., 2012, Torabi et al., 2015b). The other type of zirconia that can be used include the translucent zirconia which offers aesthetics to the restoration because they permit the underlying tooth-coloured substructure to influence the overall restoration aesthetics. In conclusion they can be used to construct all-zirconia restorations which provide both aesthetics and strength (Rinke and Fischer, 2013).

3.2 Aims and objectives

The aims of this *in vitro* study were to investigate if the firing cycles used for placement of veneering ceramic over zirconia frameworks had any effect on the internal and marginal fit of all ceramic bridges, and to determine whether the different thicknesses of zirconia used in the manufacture of zirconia frame works and all zirconia bridges could also impact upon internal and marginal fit of the restoration.

3.3 Material and Methods

Tooth preparation and quality control

Ideal tooth preparations were achieved for a three unit all zirconia bridge in the first laboratory study; these were quality controlled for total occlusal convergence and finish line chamfer depth according to predetermined standards. The same preparations were used in this laboratory study.

Digital Impression and all zirconia bridge manufacture

The Digital files produced from scanning the prepared teeth in the first laboratory study were used to produce 45 identical non-sectioned SLA models (Check Models, In'Tech Industries, Inc. USA) for this study. The data captured by the Lava™ Chairside Oral Scanner (Lava™ C.O.S, 3M ESPE, Seefeld, Germany) from the first study was also used to construct 45 zirconia based restorations in this study: 15 all zirconia bridges and 30 zirconia frameworks (Figure 3.1). The identical all zirconia bridge design created and steps followed in the first study were used for the order of the all zirconia bridges (n = 15) in this study; for the 30 zirconia frameworks in this study the same steps were again followed with the exception that when the zirconia frameworks were ordered the “Reduced crowns” option was selected from the “Prosthetic sub-type” drop box for the abutments and the “Reduced pontics” option selected for the pontic. These components were then linked together to create a zirconia bridge framework.

Figure 3.1 All zirconia three unit bridge and zirconia framework.

The all zirconia bridge and zirconia framework designs were individually sent to the 5 axis milling machine to mill 15 identical all zirconia bridges and 30 identical frameworks from semi-sintered zirconia multi blocks (3M ESPE, Seefeld, Germany, and LOT No. 498385 X 12 blocks). The semi-sintered all zirconia bridges and zirconia frameworks were placed in a custom furnace (Lava™ furnace 200, (3M ESPE, Seefeld, Germany) to fully sinter at 1500° C for 4 hours 48 minutes (LAVA 1500, Non-shaded). The same cycle settings were used for the all zirconia bridges and the frameworks.

<u>Veneering (pressing technique)</u>

To investigate whether the veneering process and subsequent firing cycle could have an effect on the fit of the zirconia based bridges, 15 of the 30 fully sintered zirconia frameworks were randomly selected to undergo ceramic veneering.

To ensure that all the veneered bridges had a final morphology and identical dimensions to the all-zirconia bridges, a wax-up technique was used. For this an addition-cured silicone impression (AFFINIS® putty soft, Coltène, LOT NO. 38620) was taken in a sectional metallic impression tray, of one of the first all zirconia bridges made for this study. For each zirconia framework, thereafter, molten pink wax (modelling wax, ANU TEX, LOT NO. 717308) was poured into the silicone impression and the zirconia framework gradually inserted until the molten wax reached the margins of the zirconia framework retainers and the retainer margins were at the corresponding position of the impression. Once the wax had cooled and solidified the waxed frameworks were removed from the impression and three 5.0 mm length wax sprues (3.0 mm diameter, S-U-WACHSDRAHT, LOT 62730019) were attached to each retainer and pontic (Figure 3.2). Each waxed and sprued framework was then weighed to ensure consistency (each weighing 1.2g) and to ensure that the correct number of pressable ceramic ingots were chosen (n = 2).

The sprued waxed frameworks were then mounted on an investment mount and placed in an investment ring. A graphite free, phosphate bonded investment material (VITA PM Einbettmasse, 2X100g, LOT NO. 3953346, VITA PM Investment Liquid and LOT 38650) was then mixed under vacuum according to the manufacturer's instructions. This was initially painted over the waxed frameworks using vibration to avoid creation of any air bubbles and the remaining material poured into the investment ring until full, embedding the waxed zirconia framework. After 30 minutes setting time the investment ring was place in a preheated furnace (model BOF 11/13, CARBOLITE®) at a temperature of 850° C for 75 minutes for wax burnout. Each ring was then removed from the furnace and immediately two veneering ceramic ingots (VITA PM9, press pellet, LOT NO. 3953346) were placed at the entrance to the sprue holes together with a disposable press plunger and placed in a preheated (700° C) pressing furnace (DeguDent Profire® press, DENTSPLY). The furnace was pre-programmed to the recommended firing cycle (start temperature 700° C, heating rate 50° C/min, end temperature 1010° C, holding time 22 mins and pressing time 10 minutes under a pressure of 3 bar).

Once the pressing program had terminated the investment ring and contents were removed and allowed to slowly cool down. The veneered zirconia frame works were then carefully divested ensuring no damage to the pressed bridge (Figure 3.2 A & B). The sprues were removed using a diamond disc without applying heavy pressure, keeping a short sprue stub which was removed with a fine-grit sharp diamond bur. Care was taken not to over-heat the veneer ceramic so as not to create micro-cracks. The zirconia bridges (all zirconia and veneered zirconia frameworks) were not glazed.

Figure 3.2 (A) Zirconia framework with waxed-up bridge contour with sprues, (B) pressed ceramic on zirconia framework (before finishing)

Bridge cementation

The study sample therefore consisted of three groups (15 all zirconia bridges, 15 un-veneered zirconia frameworks and 15 veneered zirconia frameworks). Each zirconia restoration was randomly appointed to one SLA model. RelyX™ Unicem 2 Clicker™ (3M ESPE, Seefeld, Germany, LOT No. 517676) self-adhesive Universal Resin Cement was used as the luting cement. All-zirconia bridges were cemented on their SLA models following manual mixing of the base and catalyst luting cement into an even mix and application to the entire fit surface of each retainer as recommended by the manufacturer. A custom made constant force device was used to seat each bridge using a 30 N force for at least 5 - 6 minutes (Figure 3.3). Using a rectangular, horizontal metal rod, the custom made cementation device ensured a constant vertical force was applied across both abutment-retainers and the pontic at the same time. The device was tested on numerous occasions using a weighing scale (Avery Berkel, Model TB061) to make sure that the force application was correct and reproducible. The excess cement was cleared away from the retainer margins using a metallic instrument during the setting time of the cement (as recommended by the manufacturer). After five minutes of force application the weights were removed and no light cure was used in this laboratory study.

Preparation for, and SEM observation

For SEM analysis of the internal and marginal fit of the cemented restorations, the same embedding and sectioning protocol was used as for the first laboratory study. However, a different SEM machine was used in this study but at exactly the same settings (SEM, HITACHI S - 4800).

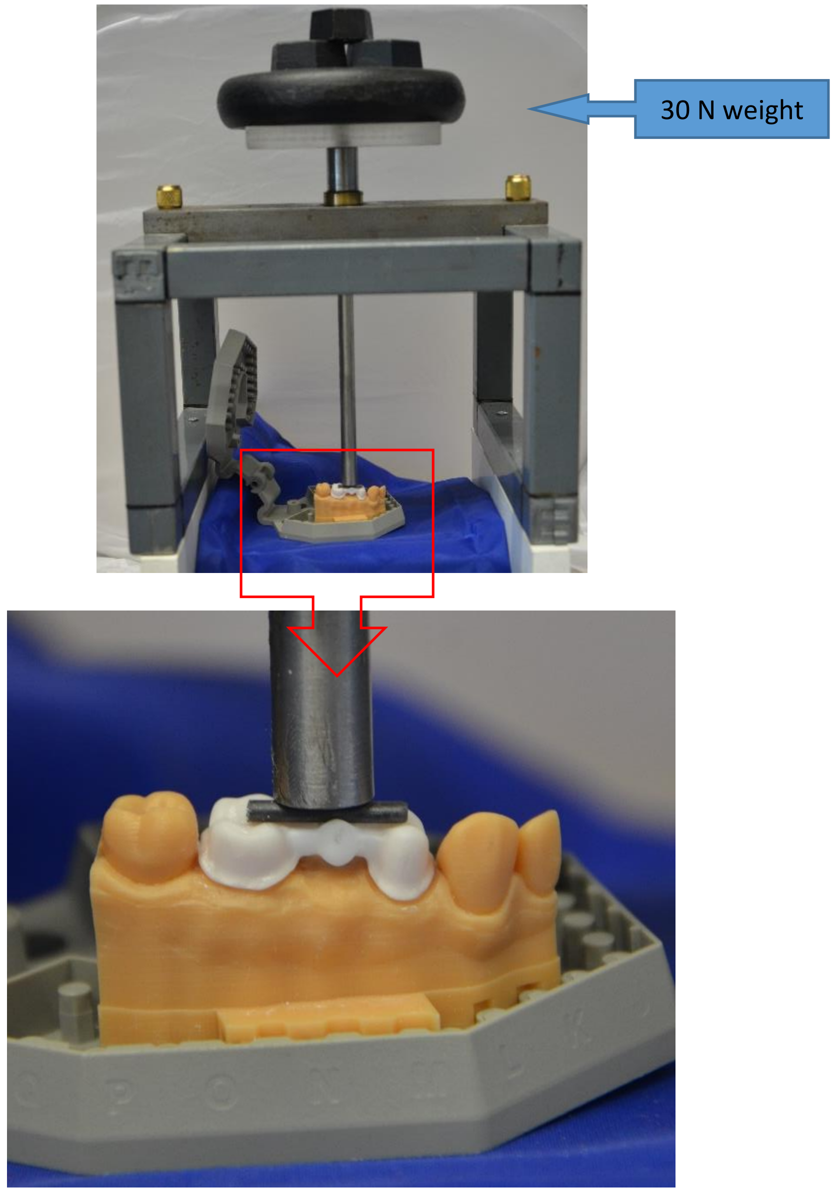


Figure 3.3 Force application device for cementation of the zirconia based bridges

Statistical analysis

For each bridge type (all zirconia, zirconia framework and veneered zirconia) identical measurements (as in the first in vitro study) were taken for the internal and marginal fit determination. For both parameters (internal and marginal fit) the mean value and standard deviation (taken from both abutment-retainers) for each restoration type was determined. One way ANOVA and post hoc test (Bonferroni) were used to assess the means of internal fit of the three types of bridges, and for the marginal fit Friedman test and Wilcoxon Signed-Rank test (because the data was non-parametrically repeated) was used to determine if there was any significant difference between each bridge type. This was then repeated separately for the premolar abutment-retainer fit and the molar abutment-retainer fit for each bridge type and between bridge types (all zirconia, zirconia frameworks and veneered zirconia) using t-test (IBM® SPSS® 21).

3.4 Results

Internal fit

The mean value for the internal fit for the all zirconia bridges was 88.6 µm (min 83.0 µm, max 109.0 µm, SD ± 0.25), for the zirconia frameworks 88.4 µm (min 83.0 µm, max 108.0 µm, SD ± 0.24) and for the veneered zirconia frameworks 118.2 µm (min 112.0 µm, max 139.0 µm, SD ± 0.27) (Figure 3.4). One way ANOVA showed a statistically significant difference in the internal fit between the cemented bridges ($p \leq 0.05$); post hoc (Bonferroni) test showed that the internal fit of the veneered zirconia bridges was significantly worse ($p \leq 0.05$) than the all zirconia bridges and the zirconia frameworks ($p \leq 0.05$). No statistically significant difference was found between the internal fit of the all zirconia bridges and the un-veneered zirconia frameworks ($p = 1$).

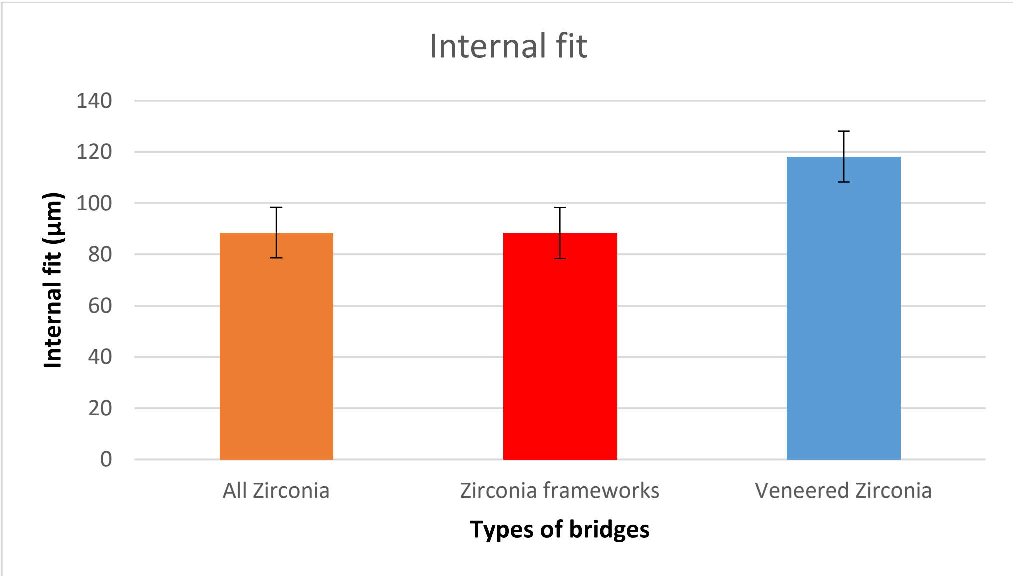


Figure 3.4 Mean (and SD) for internal fit of three different types of zirconia bridges.

Molar abutment-retainer and premolar abutment-retainer

The molar abutment-retainers internal fit were compared with the premolar abutment-retainers for each bridge type (all zirconia, zirconia frameworks and veneered zirconia frameworks) and for the same abutment-retainers for the different bridges.

In the case of all zirconia bridges the mean value internal fit of the molar abutment-retainers was 88.6 µm (min 82.0 µm, max 109.0 µm and SD ± 6.91) and for the premolar the mean was 88.6 µm (min 80.0 µm, max 109.0 µm and SD ± 6.91). In zirconia frameworks the mean value of internal fit of the molar abutment-retainer was 88.4 µm (min 83.0 µm, max 109.0 µm and SD ± 7.05) and the premolar the mean value was 88.3 µm (min 82.0 µm, max 109.0 µm and SD ± 7.05). The veneered zirconia frameworks molar retainers mean reading was 118.3 µm (min 110.0 µm, max 139.0 µm and SD ± 7.97) whilst the premolar results were mean 118.3 µm (min 109.0 µm, max 140.0 µm and SD ± 7.97). The t-test showed that for each type of bridge (all zirconia, zirconia framework and veneered zirconia) there was no statistically significant difference ($p = 1$) between the internal fit of the retainers on the premolar and molar teeth.

Comparison of the internal fit for the molar abutment-retainers from all three bridge types showed that there was a statistically significant difference between the three types ($p \leq 0.01$). Similarly comparison of the internal fit for the pre-molar abutment-retainers for the three bridge types also showed a statistically significant difference ($p \leq 0.05$). The difference was due to the veneered zirconia retainers (molar and pre-molar) which had worse internal fit compared to the all zirconia and zirconia frameworks; there was no statistically significant difference between the corresponding abutment-retainers for the latter two ($p = 0.09$).

Marginal fit

Where the marginal fit was concerned, the all-zirconia bridges mean marginal gap was 28.1 µm (min 27.0 µm, max 29.0 µm and SD ± 0.7), the zirconia frameworks mean marginal gap was 28.0 µm (min 26.0 µm, max 29.0 µm and SD ± 0.72) and for the veneered zirconia frameworks the mean marginal gap was 48.0 µm (min 47.0 µm, max 49.0 µm and SD ± 0.74) (Figure 3.5). Friedman statistical analysis was performed on the marginal fit readings, this showed that there was a statistically significant difference between the bridge types ($p \leq 0.005$). Wilcoxon signed-rank test showed that there was a statistically significant difference between the marginal fit of the all zirconia bridges and the veneered zirconia framework ($p \leq 0.05$) and between the zirconia frameworks and veneered zirconia frameworks ($p \leq 0.05$). Whilst the marginal fit of the veneered zirconia frameworks were wider than the all zirconia bridges and zirconia frameworks, no difference was found between the latter two ($p = 1$).

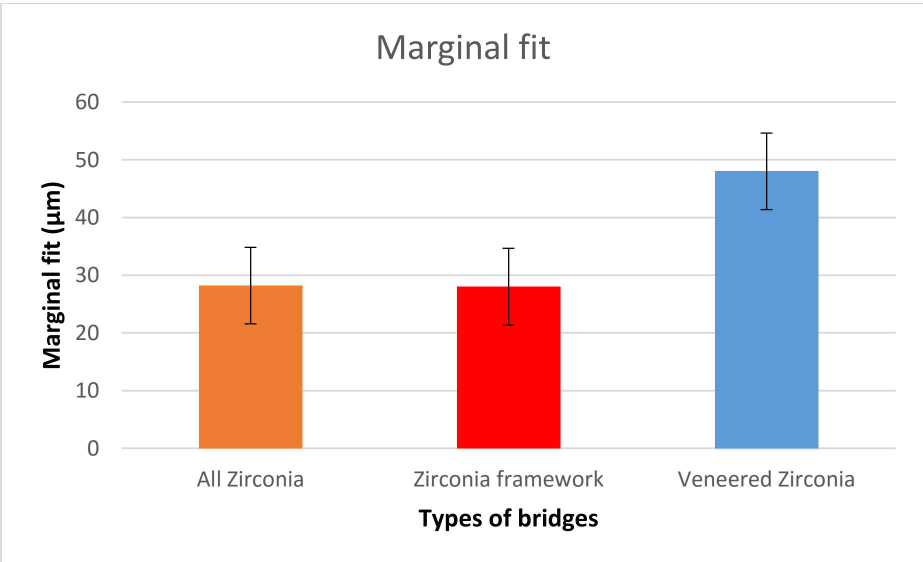


Figure 3.5 Mean (and SD) for marginal fit of three types of zirconia bridges.

No statistically significant differences were found when the marginal fit of the molar and premolar abutment-retainers were compared for the same bridge type ($p = 1$).

When the molar and premolar abutment-retainer marginal fits were separately compared for each bridge type a statically significant difference was found between the all zirconia bridges and the veneered zirconia frameworks and between the zirconia frameworks and the veneered zirconia frameworks ($p \leq 0.05$), with the veneered zirconia framework having a wider marginal fit. All zirconia bridges and zirconia frameworks showed no statistically significant difference between the marginal fit of the two types of bridges ($p = 1$).

3.5 Discussion

Internal and marginal fit are both important factors to consider when constructing and fitting any indirect dental restoration; they can be affected by aspects of the tooth preparation, clinical techniques (e.g. impression technique) and various stages in the manufacturing process (Martins et al., 2012).

In this study all such variables have been controlled to ensure that the only variable was in the manufacture process. The same digital files of the prepared teeth from laboratory study 1, which were obtained using the Lava™ Chairside Oral Scanner (Lava™ C.O.S, 3M ESPE, Seefeld, Germany), were used in this laboratory study to produce the un-sectioned SLA models (45 models) and design the zirconia restorations (15 all zirconia bridges and 30 zirconia frameworks).

The variables investigated were the firing cycles and zirconia thickness. During the first firing cycle of the semi-sintered bridges the restorations shrink by approximately 20.0 – 30.0 % in volume (Suttor et al., 2001, Beuer et al., 2008c), therefore it is possible that placing the framework back in a hot furnace on two further occasions to burn the wax off in preparation for the veneering process and for the injection veneer process itself, could affect the dimensions of the restoration and hence fit (Kunii et al., 2007, Romeo et al., 2009, Cho et al., 2012, Pak et al., 2010). In this regard, in addition the difference in volume of a zirconia framework and an all zirconia bridge could impact upon the amount of sintering shrinkage and fit of the restoration.

The results obtained from this study showed that firing cycles led to a significant difference in the internal and marginal gaps between the veneered zirconia frameworks and the all zirconia bridges and frameworks ($P < 0.05$). On the other hand, the difference in the thickness between the all zirconia bridges and zirconia framework did not show any significant difference ($P = 1$), the mean results of the internal and marginal fit were 88.6 µm and 28.1 µm for the all zirconia bridges and 88.4 µm and 28.0 µm for the zirconia frameworks. The results of the all-zirconia bridges and zirconia frameworks from this laboratory study are comparable with the results of the first laboratory study (mean internal fit = 90.4 µm and mean marginal fit 28.4 µm).

As in the previous study, RelyX Unicem (dual cured self-etching resin luting cement, 3M ESPS) was used to cement the zirconia based restorations in this study. A 30 N constant vertical force was used to cement the zirconia bridges and frameworks using a custom made force device, which is consistent with the mean force applied by practitioners in the first laboratory study in this thesis and was within the range of forces applied by practitioners in previous studies (Black and Amoore, 1993, Mustafa et al., 2010). In this study the force was applied for five minutes which is sufficient to allow for the chemical cure of the luting cement (RelyX Unicem, 3M ESPE) as the margins of the bridges were not light cured. Clinically, dentists are unlikely to maintain such a force over such a prolonged period of time, as demonstrated in study 1. Alternatively, they are likely to seat the bridge, remove excess cement whilst maintaining force and then light cure the margins. However, the cementation process used in this study ensured an identical cementation force and technique was applied to all the bridges which was monitored throughout the study.

The same procedure that was used in the first laboratory study to measure the internal and marginal gaps, namely SEM analysis, was used in this study and again the greatest readings were recorded occlusally followed by the axial walls, with the smallest reading in relation to the marginal gaps. As with the first laboratory study the occlusal and axial reading were dealt with as one reading and separate from the marginal gap.

In this study the results showed an increase in the internal and marginal fit following the additional two firing cycles (de-waxing and veneering) for the veneered framework: the mean internal gap was 118.2 µm and the mean marginal gap was 48.0 µm for the veneered framework compared to 88.4 µm and 28.0 µm for the un-veneered zirconia frameworks. In reality, this could be exacerbated by an additional firing cycle for glazing however the result of one previous study has shown that glazing had no effect on the marginal fit (Vigolo and Fonzi, 2008). The pre-sintered zirconia frameworks are stained using dyeing liquid, and this requires different firing cycles than the cycle used in this experiment. When a zirconia is stained using the dyeing liquid, the Lava™ Classic firing program is chosen which sinters the zirconia framework at 1500° C for eight hours and 30 minutes. The longer firing cycle could also have an effect on the internal and marginal fits.

Although there was a difference in fit between the veneered and un-veneered zirconia frameworks and all zirconia restorations, all are considered to be within or lower than the acceptable clinical range between 80.0 µm to 150.0 µm (McLean and von Fraunhofer, 1971, Martinez-Rus et al., 2011). Metal ceramic restorations have historically been considered the gold standard restoration (Sundh et al., 2005), and studies comparing CAD CAM bridges with metal ceramic have shown comparable fit in the order of 75.0 µm to 81.3 µm (Reich et al., 2005a, Reich et al., 2008, Song et al., 2013).

Although a number of studies have now investigated the effect of ceramic veneering on the internal and marginal gaps, the results appear to conflict (Table 3.1). Some of the studies found that the additional firing cycles needed led to an increase in the internal and marginal gap, other studies found no effect and finally two studies found that firing cycle led to a decrease in the gap.

In this laboratory study, fully anatomical three unit bridges were constructed over an ideal preparation of plastic teeth whereas most other studies have been carried out on single crowns (Lee et al., 2008, Romeo et al., 2009, Pak et al., 2010, Euan et al., 2012). Some studies prepared extracted natural teeth (Romeo et al., 2009, Pak et al., 2010, Euan et al., 2012) and some used non-anatomical cylindrical metal studs as abutments (Kunii et al., 2007, Komine et al., 2007, Bhowmik and Parkhedkar, 2011, Miura et al., 2014) which could have had an impact on the results obtained. These studies are summarised in Table 3.1.

It is clear that only three studies have investigated long span bridges. One of these showed an increase in the cement gap in three, four and five unit restorations after two firing cycles (Kunii et al., 2007), one showed no effect of two firing cycles on the internal and marginal fit of four unit restorations (Vigolo and Fonzi, 2008) and one found a decrease in the fit of four unit restorations after four firing cycles (Kohorst et al., 2010). It is interesting to note that the two studies (one looking at four unit restorations and one single unit restorations (Kohorst et al., 2010, Miura et al., 2014)) that found a decrease in fit after additional firing cycles, used the highest number of firing cycles (four) compared to the majority that looked at two firing cycles (Table 3.1). The explanation for the decrease in fit may therefore be due to additional shrinkage during the extra firing cycles.

Although it could be argued that the increase in the marginal gap that occurred in this study following the firing for the ceramic veneering could affect the longevity of the restoration, it is unlikely as the gaps were comparable or lower than those previously reported, and in clinical trials the survival rate of all ceramic restorations has been shown to be comparable with conventional metal ceramic bridges (Martins et al., 2012, Rinke et al., 2015) in this respect.

Table 3.1 Different studies investigating the effect of veneering on internal and marginal gap

Study	No. of samples	Type of abutment	Types of restorations (units)	No. of firing cycles	Method of measurement	Effect of firing on Inter/Marg
(Kunii et al., 2007)	12	Metal	1, 3, 4, 5	2	Microscope (digital)	Increased
(Lee et al., 2008)	20	Plastic	1	2	Microscope (?)	Increased
(Romeo et al., 2009)	20	Natural tooth	1	2	Photos – Software	Increased
(Pak et al., 2010)	20	Natural tooth	1	2	Microscope (light)	Increased
(Cho et al., 2012)	40	Ivorian tooth	1	5	Microscope (light)	Increased
(Euan et al., 2012)	20	Natural teeth	1	2	Microscope (stereo)	Increased
(Torabi et al., 2015b)	30	Metal	1	2	Microscope (digital)	Increased
(Komine et al., 2007)	24	Metal	1	2	Microscope (laser)	No effect
(Vigolo and Fonzi, 2008)	45	Acrylic	4	2	Microscope (SEM)	No effect
(Tao and Han, 2009)	15	Plastic	1	2	Profile projector	No effect
(Bhowmik and Parkhedkar, 2011)	15	Metal	1	3	Microscope (optical)	No effect
(Kohorst et al., 2010)	20	Plastic	4	4	Microscope (light-optical)	Decreased
(Miura et al., 2014)	15	Metal	1	4	Projector	Decreased

The studies in Table 3.1 have all examined the effect of veneering ceramic using either the press-over (pressable) technique or conventional free-hand layering technique. More recently a new veneering technique called CAD-on has been introduced to fabricate the veneering layer using Lithium-disilicate (Beuer et al., 2009f, Torabi et al., 2015b). When the CAD-on veneering technique was compared with the layering and press-on veneering technique, the results showed that all three veneering techniques led to an increase in the marginal fit of the zirconia based restoration compared with the coping beneath; the zirconia coping mean gap was 35.0 µm, which increased to 63.1 µm with the layering veneer technique, 50.6 µm using the pressing technique and finally 51.5 µm with the CAD-on veneering technique (Torabi et al., 2015b). Although all veneering techniques led to an increase in fit all of them produced small marginal gaps and clinically acceptable results.

3.6 Conclusions

Within the limitation of this study, the following conclusions can be drawn:

1. The additional firing cycles used to veneer the zirconia frameworks have an effect on the internal and marginal gaps, by leading to an increase in both.

2. The difference in the thickness of zirconia (all zirconia and zirconia frameworks) has no effect on the internal and marginal fit of the restoration.

3. All zirconia bridges, zirconia frame works and veneered zirconia frameworks, produce clinically acceptable internal and marginal gaps.

Chapter 4

Laboratory study 3

Three unit all zirconia bridges versus four unit all zirconia bridges

Laboratory study 3

Three unit all zirconia bridges versus four unit all zirconia bridges

4.1 Introduction

Since zirconia-based ceramics were introduced they have demonstrated superior mechanical and aesthetic properties compared to other ceramics. Whilst initially used to construct inlays and single unit restorations zirconia has increasingly been used for longer span bridges (Abduo et al., 2010) due to its strength. As such long span zirconia bridges (e.g. three, four and five unit bridges) are becoming the subject of a number of investigations. Some studies have compared the fit of single unit crowns with that of bridges (Beuer et al., 2009e, Lee et al., 2013a, Anunmana et al., 2014) (see discussion), a number have looked at the fit of bridges with one specific span length (Komine et al., 2005, Reich et al., 2005a, Bindl and Mormann, 2007, Gonzalo et al., 2008, Reich et al., 2008, Vigolo and Fonzi, 2008, Att et al., 2009, Beuer et al., 2009a, Beuer et al., 2009d, Dittmer et al., 2009, Gonzalo et al., 2009, Kohorst et al., 2009), but only two have compared the effect of increasing the span of bridges on fit in the same study (Tinschert et al., 2001b, Lee et al., 2013a). The results from these two studies suggest a trend toward a deterioration in fit with increasing span length. However this did not reach a statistically significant level in the first study (Tinschert et al., 2001b). The other study by Lee et al., 2013 showed that there was statistically significant difference between single unit crown, four unit bridge and six unit bridges (Lee et al., 2013a).

As pre-sintered zirconia is affected by approximately 20.0 – 30.0 % shrinkage on firing (Suttor et al., 2001) it could be expected that this would have a bigger impact upon the fit of longer span bridges. Furthermore, veneering the zirconia frameworks has been shown in Laboratory Study 2 in this thesis to have an impact on the fit of three unit bridges, it is possible that this impact could again be exacerbated with longer span bridges. For those studies that have examined at four unit bridges, no consensus was reached on the impact of ceramic veneering, with one showing an increase, one showing no impact in marginal gap and the other showing a decrease in marginal gap. (Kunii et al., 2007, Vigolo and Fonzi, 2008, Kohorst et al., 2010).

As internal and marginal gaps have the potential to affect the survival and longevity of the indirect dental restoration (Subasi et al., 2012, Lee et al., 2013a), and due to the paucity in evidence assessing the impact of altering the length of the span of the bridge has on this, there is a need for further investigation.

4.2 Aims and objectives

The aim of this laboratory study was to compare the effect that the length of the span of all zirconia bridges (three unit and four unit) made using the Lava COS intra oral scanner, has on the internal and marginal fit.

4.3 Material and Methods

Tooth preparation and Quality control

Two new plastic teeth were selected and prepared for a four unit bridge (abutment teeth 14 and 17 and pontics teeth 15 and 16). The same "quality control" as used in the first laboratory study were followed to ensure that all the requirements of standardised tooth preparations were achieved (taper of the teeth, finish-line and occlusal reduction). The mean total occlusal convergence angle for tooth 14 was 11.6° (min 11.2° – max 11.8°) and for tooth 17 was 11.5° (min 11.2°- max 11.7°), the mean chamfer depth around tooth 14 was 1.1 mm (min 1.0 mm – max 1.4 mm) and tooth 17 was 1.2 mm (min 1.0 mm – max 1.5 mm).

Digital Impression and SLA models

Once the ideal tooth preparations were achieved for the four unit bridge and confirmed through the quality control process, the prepared teeth on the original model were scanned with the Lava™ Chairside Oral Scanner (Lava™ C.O.S, 3M ESPE, Seefeld, Germany) according to the manufacturer's instructions to produce 15 (four unit) identical non-sectioned Stereolithography models (SLA models, In'Tech Industries, Inc. USA). The same procedure that was used in the first laboratory study for the three unit bridges was used for the four unit bridge abutments scanning.

Bridge design and fabrication

The data captured of the prepared teeth (14 and 17) were used to design the four unit all zirconia bridges in the CAD system, the same settings that were used for the three unit bridges were used for the four unit bridges, to ensure that the bridges were identical from a production point of view and that the only difference was in the length of the span of the bridge (die spacer 0.095 mm extra vertical (occlusal), 0.075 mm extra horizontal (buccal, mesial, distal and lingual) and minimum coping thickness 0.5 mm). Semi-sintered zirconia multi blocks were used to fabricate the all-zirconia bridges (3M ESPE, Seefeld, Germany, LOT No. 470281 X 3 and 472678 X 5) using a five axis CAM milling machine and dry milling process machine (Lava™ CNC 500 Milling System, 3M ESPE). The semi-sintered all-zirconia bridges were placed in a custom furnace (Lava™ furnace 200, (3M ESPE, Seefeld, Germany) to fully sinter the zirconia framework at 1500° C for 4 hours 48 minutes (LAVA 1500, Non-shaded).

The results for the internal and marginal fit of the three-unit all-zirconia bridges determined in the second laboratory study were used in this study.

Bridge cementation

The 15 four-unit all-zirconia bridges were cemented permanently to their designated un-sectioned SLA models. The same steps that were used in the second laboratory study for cementing the three unit all-zirconia bridges were used in this laboratory study (See laboratory study two). RelyX™ Unicem 2 Clicker™ (3M ESPE, Seefeld, Germany, LOT No. 517676) self-adhesive Universal Resin Cement was used as the luting cement. Zirconia bridges were cemented on their SLA model using a constant vertical seating force of 30 N for five minutes across both the abutments-retainers and pontics, using the custom made force device that was used in the previous studies. The excess cement was cleared away from the abutment-retainer using a metallic instrument during the setting time of the cement (Figure 4.1).

Figure 4.1 One of the four unit bridges (left) and three unit bridges (right) cemented on the corresponding SLA models

Preparation for, and SEM observation

The SLA models and the cemented four-unit all-zirconia bridges were embedded in Orthoresin (self-curing, DENTSPLY, DeguDent Gmbh, Germany, and LOT NO. 13FEB096 (powder), 12AUG045 (liquid)) as in the first study to ensure that the bridges and SLA models did not fragment during the sectioning process. As in the first study with the three unit bridge, each model was sectioned bucco-lingually and mesio-distally through each retainer using an IsoMet® 5000 Linear precision saw (Buehler®, a division of Illinois Tool Works Inc.) with an

IsoMet® diamond wafering blade (178.0 mm x 0.6 mm, Buehler®) under water coolant, for subsequent examination under the Scanning Electron Microscope (SEM). Each retainer and abutment tooth was therefore sectioned into 4 segments.

SEM observation

Sectioned samples from the four-unit all-zirconia bridges were mounted on aluminium studs using double sided carbon tape as was done in the first study with the three-unit bridges, then painted with silver conductive paint (conductive pen, MG chemicals). The samples were then examined under the Scanning Electron Microscope (SEM, HITACHI S - 4800) at 150x magnification operating at acceleration voltage of 15 kV (to measure the cement space internally and marginally). The images were viewed on a 19” flat screen using Microscope Control software. For each bridge, measurements of marginal gap were made at eight predefined segments (four from the premolar and four from the molar). Each segment had two walls, similar to the three unit bridges in the previous studies (see laboratory study two).

Statistical analysis

For the four-unit all-zirconia bridges, identical internal and marginal cement gaps measurements were recorded and used to check if there was any statistical differences between the two bridge types. One way ANOVA was used to assess the internal and marginal fits of the four unit all zirconia bridges (IBM® SPSS® 21). The results obtained for the three-unit bridges determined and used in the previous laboratory studies (laboratory study two) were also used to compare with the four-unit bridge results obtained in this laboratory study.

This was repeated separately for the premolar abutment-retainer fit and the molar abutment-retainer fit for each bridge type and between bridge types (three unit and four unit all zirconia bridges) using one-way ANOVA (IBM® SPSS® 21).

4.4 Results

Internal fit

The mean internal fit of the three-unit all zirconia bridges was 88.4 µm (min 82.0 µm, max 108.0 µm and SD ± 6.9) and it was 88.5 µm (min 83.0 µm, max 109.0 µm and SD ± 7.0). For the four-unit all zirconia bridges. There were no statistically significant differences between the two types of bridges ($p = 0.79$) (Figure 4.2).

Molar abutment-retainer and premolar abutment-retainer

The molar and premolar abutment-retainers were compared from the three unit bridges with each other using one-way ANOVA to determine if there were any statistically significant differences between the abutment-retainers. The results showed that there were no statistically significant differences between the two abutment – retainer tooth types ($p = 0.34$). For the molar and premolar abutment-retainers of the four unit bridges, the results showed that there were no statistically significant differences between the two abutment – retainers tooth types ($p = 0.57$)

When considering the molars abutment-retainer results, there were no statistically significant differences for the two different span bridges ($p = 0.42$). For the premolar abutment-retainer internal fit results the one-way ANOVA showed that there were no statistically significant differences for the results obtained from the two different span bridges ($p = 0.28$).

Marginal fit

The mean marginal fit of the three-unit all-zirconia bridges was 28.3 µm (min 26.0 µm, max 29.0 µm and SD ± 0.7) and 28.4 µm (min 27.0 µm, max 29.0 µm and SD ± 0.7) for the four unit all zirconia bridges. The one-way ANOVA statistical test showed that there was no statistically significant difference between the marginal fit of the three and four unit bridges ($p = 0.35$) (Figure 4.2).

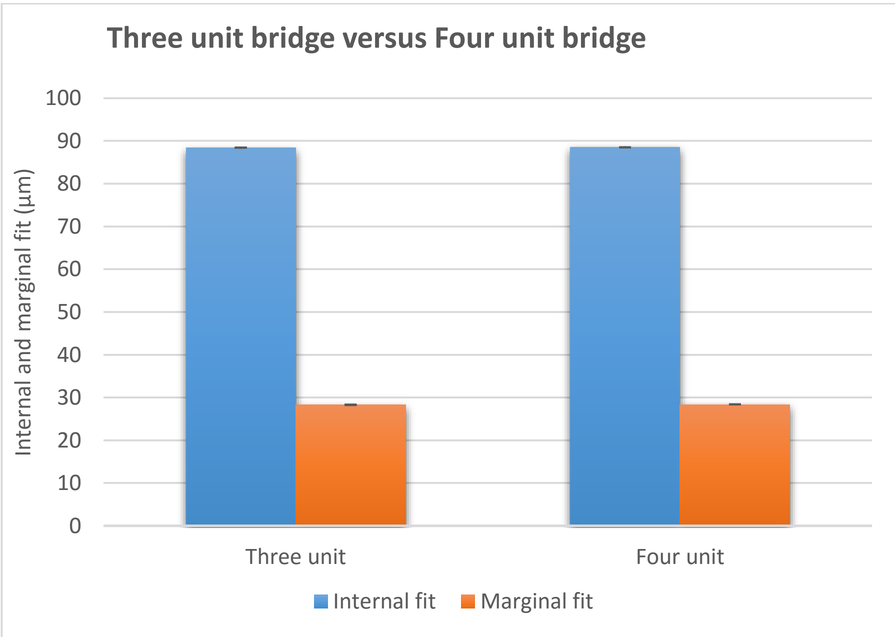


Figure 4.2 A chart comparing the internal and marginal fit of the three and four unit bridges

Molar abutment-retainer and premolar abutment-retainer

A one-way ANOVA of the marginal fit results demonstrated that the three-unit bridge results showed that there was no statistically significant difference between the molar and premolar abutment-retainers ($p = 0.43$); the same findings were found for the four-unit bridge abutment - retainers (molar and premolar) ($p = 0.19$).

The molar abutment-retainer from both types of bridges marginal fit results showed that there were no statistically significant difference in relation to marginal fit ($p = 1$); identical results were obtained for the premolar abutment-retainers ($p = 1$).

4.5 Discussion

Both internal and marginal fits can be affected by many factors such as the CAD CAM system used, sintering status of the zirconia when milled and the span length of the constructed indirect dental restoration, to name but a few (Abduo et al., 2010).

The aim of this study was to compare the internal and marginal fits of different span length zirconia bridges. The bridges constructed in this laboratory study were all-zirconia three-unit and four-unit bridges; no veneered frameworks were used in order to eliminate any effect of the ceramic veneering process on the internal and marginal fit of the bridges. Both three - and four - unit bridges were constructed following exactly the same process as used in the first and second laboratory studies and randomly allocated to the SLA models so that the only difference between the bridges was in the number of units. The span lengths were chosen because these are the most commonly used span lengths for bridges constructed in Dundee dental hospital (data collected over the past five years (2011 - 2015)). Longer span bridges are less common due to the greater indication for removable prostheses and the introduction of dental implants (Hemmings and Harrington, 2004).

The results of this laboratory study of both the three-unit all-zirconia bridges (mean internal gap 88.4 µm and mean marginal fit 28.3 µm) and the four-unit all-zirconia bridges (mean internal gap 88.5 µm and mean marginal fit 28.4 µm) were comparable to other studies (see Table 4.1), where the internal fit results of the studies ranged from 54.2 µm to 144.0 µm and the marginal fit ranged from 9.0 µm to 203.1 µm (Tinschert et al., 2001b, Komine et al., 2005, Reich et al., 2005a, Bindl and Mormann, 2007, Gonzalo et al., 2008, Reich et al., 2008, Vigolo and Fonzi, 2008, Att et al., 2009, Beuer et al., 2009a, Beuer et al., 2009d, Beuer et al., 2009e, Dittmer et al., 2009, Gonzalo et al., 2009, Kohorst et al., 2009, Kohorst et al., 2010, Lee et al., 2013a, Anunmana et al., 2014).

Most of the studies included in Table 4.1 investigated the fit of bridges with one specific span namely either three (n = 7 studies, 184 bridges) or four unit (n = 6 studies, 194 bridges) bridges. Thus direct comparison between studies of different span bridges without any other confounding variables such CAD CAM system used, veneering ceramic (or not), configuration (straight or curved arch) and zirconia state (milled in pre-sintered or sintered state), is difficult. Only two studies in Table 4.1 directly compared bridges of different span length within the same study (Tinschert et al., 2001b, Lee et al., 2013a), one also comparing results with single unit crowns (Lee et al., 2013a) and two further studies compared single unit crowns with longer span bridges (Beuer et al., 2009e, Anunmana et al., 2014).

When the results of the previous studies in Table 4.1 are compared, it is clear that there are large differences between their internal and marginal fit measurements. Where the minimum marginal fits are concerned, this can range from 9.0 µm to 102.0 µm, an approximately 11 fold difference between studies assessing at three-unit and four-unit bridges (Beuer et al., 2009d, Gonzalo et al., 2009, Kohorst et al., 2010). Similarly, studies have recorded large differences in maximum marginal fit, ranging from 15.0 µm to 203.1 µm for a three-unit and six-unit bridge respectively; a 13 fold variation (Beuer et al., 2009d, Lee et al., 2013a). Application of a meta-analysis to the various studies in Table 4.1 would be impossible due to the heterogeneity between the studies. However, Figure 4.3 shows the minimum and maximum marginal gap recorded in all the studies cited and shows a trend toward increased marginal gap with increasing span length.

Three studies compared single unit restorations with longer span zirconia bridges and all three showed significant increases in marginal gap with the bridges (Beuer et al., 2009e, Lee et al., 2013a, Anunmana et al., 2014). Anunmana et al. (2014), compared single crowns made separately on premolar (tooth 25) and molar (tooth 27) teeth that were subsequently linked with three unit zirconia bridges. When the same abutment teeth were linked in a bridge, they found there was a significant increase in the internal and marginal fit/gap of the three unit bridges at both premolar and molar abutments (Anunmana et al., 2014). It would appear from these studies that bridges have an inferior fit compared to single unit zirconia crowns, but the differences, whilst statistically significant, are very small and unlikely to have a clinical impact (Table 4.1).

Table 4.1 Different studies on fit of CAD CAM restorations, No. of units, configuration and measurements

FS = Fully Sintered, SS = Semi Sintered, NS = No Significance & SD = Significant Difference

Study	Sample size	No. of units	Configuration State	Measurements		CAD CAM system Zirconia (state)	Outcome
				Marg (µm)	Int (µm)		
(Tinschert et al., 2001b)	15	3, 4 and 5 unit bridges	Framework	42.9 - 46.3	--------------------------	Precident DCS system (FS)	Trend to inferior fit with longer span (NS)
(Komine et al., 2005)	48	4 unit bridge	Straight VS curved	Straight 88.0 to 113.4 Curved 96.8 to 47.3	--------------------------	Cercon, Cerec In-Lab, Xawex (SS)	Configuration influence the fit of CAD CAM bridges Curved inferior fit
(Reich et al., 2005a)	24	3 unit bridge	Straight	77.0 – 92.0	--------------------------	Digident (FS) CEREC InLab (FS) Lava (3M ESPE) (SS)	Digident inferior to the 2 other systems (SD)
(Bindl and Mormann, 2007)	36	3 unit bridge	Framework	32.0 – 129.0	80.0 – 144.0	CEREC (FS)	Good fit of CAD CAM restorations
(Reich et al., 2008)	31	4 unit bridge	Veneered	77.0 - 170.0	--------------------------	Lava (SS)	Good fit of 4 unit CAD CAM restorations
(Gonzalo et al., 2008)	20	3 unit bridge	Veneered	26.0 – 76.0	--------------------------	Procera (FS) Lava (SS)	Good fit of CAD CAM restorations
(Vigolo and Fonzi, 2008)	45	4 unit bridge	Veneered (curved)	46.3 - 65.9	--------------------------	Everest (FS) Procera (FS) Lava (SS)	Good fit of CAD CAM restorations
(Att et al., 2009)	24	3 unit bridge	Veneered	64.0 - 89.0	--------------------------	DCS,(FS) Procera, (FS) Cerec (FS)	The fit depends on the CAD CAM system
(Kohorst et al., 2009)	40	4 unit bridge	Straight	58.0 – 206.0	--------------------------	CEREC inLab,(SS) Everest, (SS) Cercon (SS)	The fit depends on the CAD CAM system

(Beuer et al., 2009e)	50 (10B&40C)	14 unit bridge 1 unit	Curved	(14) 29.0 (1) 13.0	--------------------------	Zeno (Wieland-Imes),(SS)	Good fit of CAD CAM restorations (1&14)
(Beuer et al., 2009a)	30	3 unit bridge	Framework	29.1 - 81.4	62.7 - 119.2	Etkon, (SS) CEREC InLab (SS) Cercon (SS)	Good fit of CAD CAM restorations
(Beuer et al., 2009d)	20	3 unit bridge	Framework	9.0 - 15.0	--------------------------	Lava (SS) Procera (SS)	Good fit of CAD CAM restorations
(Dittmer et al., 2009)	10	4 unit bridge	Veneered	83.5 - 105.5	54.2 - 70.1	Everest, (SS)	Good fit of CAD CAM restorations
(Gonzalo et al., 2009)	30	3 unit bridge	Veneered	9.0 – 71.0	--------------------------	Procera Lava In-ceram	Good fit of CAD CAM restorations
(Kohorst et al., 2010)	20	4 unit bridge	Framework	49.4 - 57.6	81.0 - 112.3	Cercon	Good fit of CAD CAM restorations
(Lee et al., 2013a)	30 (10 each)	1 unit , 4 and 6 unit bridges	Curved (Anterior)	(1) 85.4 -104.7 (4) 57.9- 68.9 (6) 69.53 -203.1	--------------------------	Lava	Span length influenced the fit of the CAD CAM restoration (SD) Larger span inferior fit
(Anunmana et al., 2014)	30 (10B&20C)	1 unit and 3 unit bridge Premolar and molar	Straight	(P) 43.6 (1) 46.5 (3) (M) 48.5 (1) 52.6 (3)	(P) 150.5 (1) 154.5 (3) (M) 146.5 (1) 211.5 (3)	Lava	Span length influenced the fit of the CAD CAM restoration (SD) Bridge inferior fit

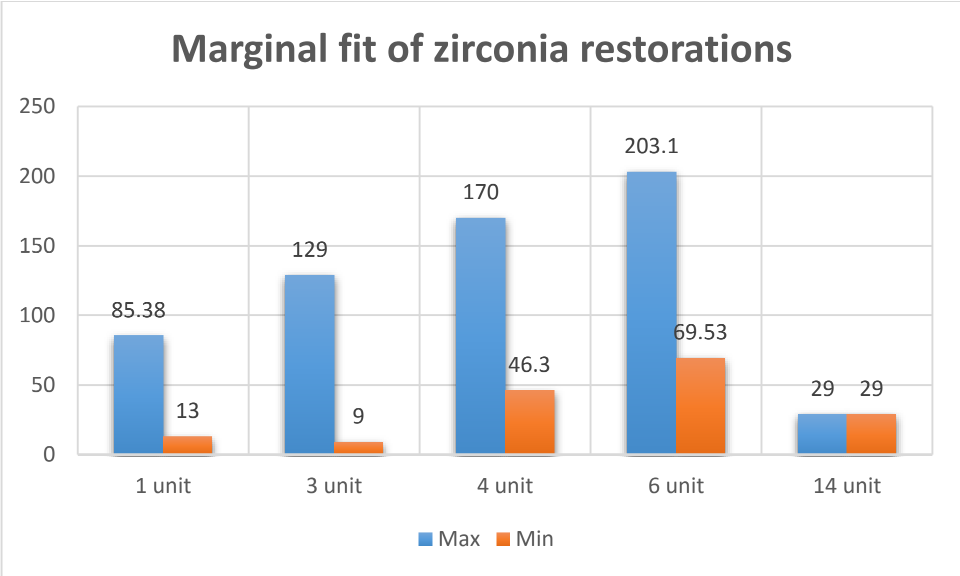


Figure 4.3 Maximum and minimum cement gaps (µm) for different zirconia restorations (studies in Table 4.1)

One factor that has been shown to influence fit of CAD CAM restorations is the configuration of the bridge. Komine et al. in 2005, when comparing four unit straight bridges with four unit bridges that span around a curved arch, found that the former had a significantly better fit (smaller marginal gap). This they attributed to the asymmetrical shrinkage of the zirconia during sintering (firing cycle) around the curvature (Komine et al., 2005).

Tinschert et al (2001) and Lee et al (2013), were the only two studies which investigated the effect of increasing span length on the fit of zirconia restorations within the same study. In the first study straight zirconia frameworks were used and they found that whilst there was no significant difference between the results of the three-, four- or five-unit zirconia frameworks (Tinschert et al., 2001b) there was a trend to increased marginal gap with increased span length. In the second study anterior curved bridges with four units (upper lateral incisor to upper lateral incisor replacing central incisors) and six units (upper canine to canine replacing four incisors) were compared and a significant difference between the four- unit and six-unit bridges were found, with the longer span bridges having a greater increase in the marginal gap (Lee et al., 2013a). The results of the latter study may not only be due to the increase in span but also the use of a greater curvature, thus supporting the findings of Komine et al., (2005) that curved restorations undergo greater distortion on firing (Komine et al., 2005).

The results that were obtained from this laboratory study comparing identically manufactured bridges, but only differing in span length, has shown that three-unit bridges and four-unit bridges did not have any statistically significant difference in relation to internal or marginal fit. Similarly, when the fit in relation to the smaller premolars and larger molar retainers were assessed separately, again there was no difference in fit due to retainer/abutment size. Thus it would appear that Lava™, 3M ESPE CAD CAM system is able to accurately compensate for zirconia sintering shrinkage in relation to bridges with significant dimensional differences, results broadly in agreement with the zirconia framework study by Tinschert et al (2001).

Whilst the zirconia milling state (fully-sintered or semi-sintered) can have an effect on the internal and marginal fit (Abduo et al., 2010, Miyazaki et al., 2013), no study has compared the two in the same study using the same CAD CAM system for bridges. Three studies compared different CAD CAM systems with some systems using fully sintered and some semi-sintered blocks for milling. Whilst the studies by Gonzalo et al., (2008) and Vigolo and Fonzi (2008) demonstrated no difference between the sintered states of the zirconia blocks (Gonzalo et al., 2008, Vigolo and Fonzi, 2008), the study by Reich et al., (2005) showed the fully sintered blocks used by the Digident CAD CAM system resulted in an inferior fit compared to the semi-sintered blocks used by the Lava system (Reich et al., 2005a). This is the reverse of what would be expected, as fully sintered blocks have already undergone the sintering shrinkage prior to milling and in theory should have a more accurate fit, the difference here may simply be due to the CAD CAM system itself being less accurate.

Finally, the internal and marginal fit results of this laboratory study were comparable to the results of the first and second laboratory studies in this thesis and previous studies of conventional restorations (Stappert et al., 2008, Baig et al., 2010).

4.6 Conclusion

Within the limitation of this study, the following conclusions can be drawn:

1. All-zirconia three- and four-unit bridges produced by Lava CAD CAM system, are within the clinically acceptable range.

2. There was no significant difference between the three- and four-unit bridges, in relation to the internal and marginal fit.

3. The span length of all-zirconia bridges is unlikely to have an impact on the internal and marginal fit of the all-zirconia bridges.

Chapter 5

Laboratory study 4

The effect of veneering on the strength of three unit zirconia based bridges

Laboratory study 4

The effect of veneering on the strength of three unit zirconia based bridges

5.1 Introduction

For the past five decades, metal ceramic has been the choice of material for extra-coronal restorations such as crowns and conventional bridge retainers (Reitemeier et al., 2013), this being because it combines the superior mechanical properties of the metal coping with the aesthetics of the veneering ceramic. Such restorations have enjoyed good long-term success / survival (Tan et al., 2004) and whilst good aesthetic outcomes can be achieved with metal ceramic restorations the demand for a "metal free approach" to dentistry and the drive for even better aesthetics, strength and biocompatibility has led to increased research effort into all ceramic restorations over the last two decades (Sundh et al., 2005, Cortellini et al., 2006).

Most recently, all ceramic restorations have involved the use of CAD CAM technology to mill zirconia into a coping similar to the metal coping of a metal ceramic crown have received attention. The zirconia coping so produced has enhanced strength (Agustín-Panadero et al., 2014), which is reported to withstand forces up to 6000 N, (Chen et al., 1999, Sundh and Sjogren, 2004, Zahran et al., 2008) but is chalky white in colour, monochromatic and opaque and hence is thought not to produce highly aesthetic restorations as a material on its own (Alghazzawi et al., 2012, Zhang et al., 2012, Xie et al., 2015). As such the zirconia is milled into a coping to provide the strength and a veneering aesthetic ceramic is applied to this to produce the characterisation and translucency required to create a restoration with a natural appearance. Whilst the principle in construction of the two types of restorations is similar the all ceramic restorations have a better translucency overall, are less opaque or "dull" in appearance and mimic better the aesthetic properties of a natural tooth compared to the metal ceramic counterpart.

Whilst zirconia is an extremely strong material, other factors can affect the strength of the completed restoration, such as application of the ceramic veneer layer. It is the latter that is most frequently implicated in the failure rate of such all ceramic restorations, and the strength is related to both the thickness of the coping / framework and veneering ceramic layer (Lund and Barber, 1992, Wakabayashi and Anusavice, 2000).

5.2 Aims and objectives

The aims of this study were therefore to investigate whether ceramic veneering of zirconia frameworks had any effect on the strength of the restoration and to determine whether there was any difference in strength between un-veneered zirconia frameworks (substructure), veneered zirconia bridges and all-zirconia bridges.

5.3 Materials and Methods

Tooth preparation and quality control

The ideal teeth preparations that were achieved in the first laboratory test were scanned, and used for this laboratory experiment.

Digital Impression and bridge manufacture

The same digital files that were used in the first and second laboratory tests were used in this laboratory test to produce 45 zirconia bridges (15 all zirconia bridges and 30 zirconia frameworks). The same settings were used for these bridges in the CAD system (die spacer 0.095 mm extra vertical (occlusal), 0.075 mm extra horizontal (buccal, mesial, distal and lingual) and minimum coping thickness 0.5 mm. This process ensured the manufacture of 15 identical three-unit all-zirconia bridges and 30 identical zirconia frameworks using a five axis CAM milling machine (Lava™ CNC 500 Milling System, 3M ESPE) and dry milling process. Semi-sintered zirconia multi blocks were used to fabricate the all-zirconia bridges (3M ESPE, Seefeld, Germany, LOT No. 470281, LOT No. 472678 and LOT No. 472678). The semi-sintered all-zirconia bridges were placed in a custom furnace (Lava™ furnace 200, 3M ESPE, Seefeld, Germany) to fully sinter the zirconia framework at 1500° C for 4 hours 48 minutes (LAVA 1500, Non-shaded).

Veneering (Pressing technique)

The veneering technique used in the second laboratory test was applied in the same order to ensure that all the framework had a consistent porcelain veneer thickness.

Metal base bridge holder

An all zirconia bridge was used to construct an accurate bridge holder (Figure5.1). Molten pink wax (modelling wax, ANUTEX) was poured in the abutment retainers and once set more wax was added to connect the two abutment retainers together by a wax box which will serve as a connector and a stand for the framework. Four wax sprues (6.0 mm) were then attached to the wax bridge holder. The lost wax technique was used after investing the holder, the investment was place in a preheated furnace (model BOF 11/13, CARBOLITE®) at 750° C for the wax to melt and create a space for the nickel chrome to flow. Nickel chrome ingots were melted at 1240° C in the casting furnace (HERACAST IQ, Heraeus Kulzer GmbH, Germany) and once they were in their liquid stage the investment was removed from the de-waxing furnace to the casting furnace and the nickel chrome was poured into the investment to form the metal bridge holder, this was left aside to cool down before sectioning the investment ring.

Figure 5.1 Metal base bridge holder

Force application

Force was applied using universal testing machine (Instron 4204, 50 KN load cell, 2 mm / min). The metal base holder was placed on the Instron table, each zirconia bridge (15 frameworks, 15 all zirconia frameworks and 15 veneered zirconia frameworks) was seated on the metal base holder and a metal rod was attached to the universal testing machine sensor to apply the force on the bridge pontic. The force was placed directly on the pontic until permanent deformation occurred (Figure 5.2). The same procedure was repeated on all 45 zirconia bridges (all zirconia, frameworks and veneered zirconia frameworks) and the force applied was recorded in each occasion for each zirconia bridge.

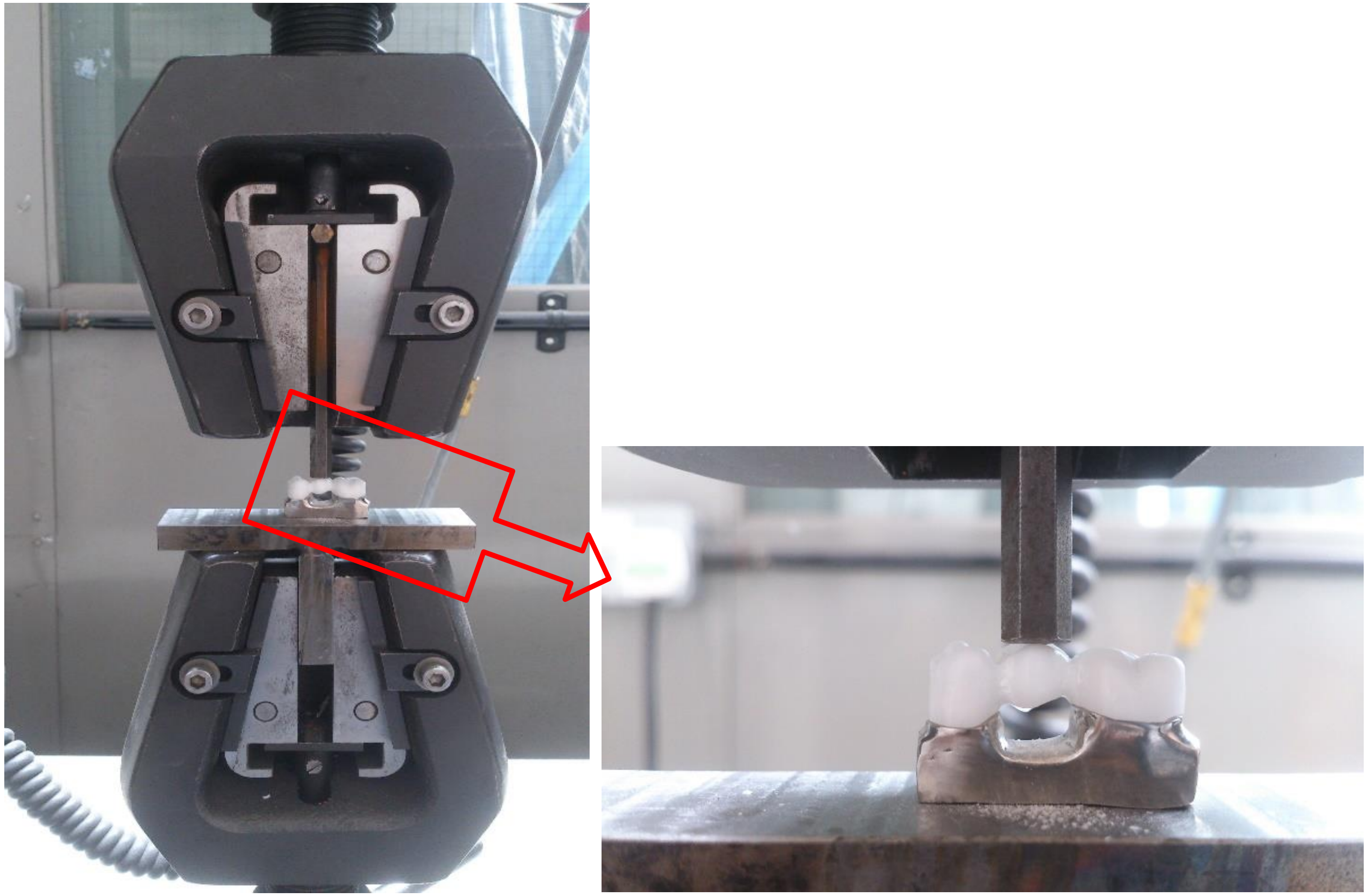


Figure 5.2 Load sensor and load application on bridge pontic

Statistical analysis

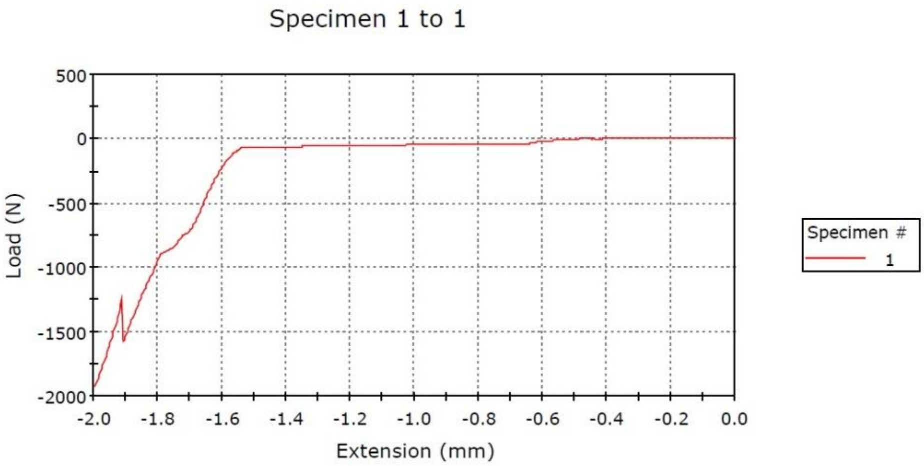
For each type of three zirconia bridges the force that led to fracture of the bridge was recorded and used to statistically test if there was any differences between the groups. One way ANOVA and post hoc testing (Bonferroni) were used to assess the forces applied by the Instron machine and if there was any significant difference between the different groups of bridges (IBM® SPSS® 21).

5.4 Results

Bridges showed different fracture behaviour when force was applied, the results showed that there was statistically significant difference between the three groups ($p \leq 0.005$).Post hoc testing however showed that there was a very highly statistical significant difference between all the three types of bridges (All zirconia, Veneered zirconia and zirconia Framework ($p = 0.000$)).

All zirconia bridges

All zirconia bridges showed the highest resistance force (N), the mean force was 1858.5 N (min 1348.0 N, max 2968.0 N, SD ± 430.5). All zirconia bridges showed an immediate fracture when the force was applied to them by the Instron machine (Figure 5.3), but it showed different fracture locations (10 in premolar, 1 molar and premolar, and 4 in the connectors, (Table 5.1)).



	Extension at Machine Break (mm)	Compressive stress at Yield (Zero Slope) (MPa)	Energy at Yield (Zero Slope) (J)
1	-----	0.25827	0.00413

	Load at Yield (Zero Slope) (N)	Load at Machine Break (N)	Load at Machine Peak Load (N)
1	-45.64000	-----	-1968.00000

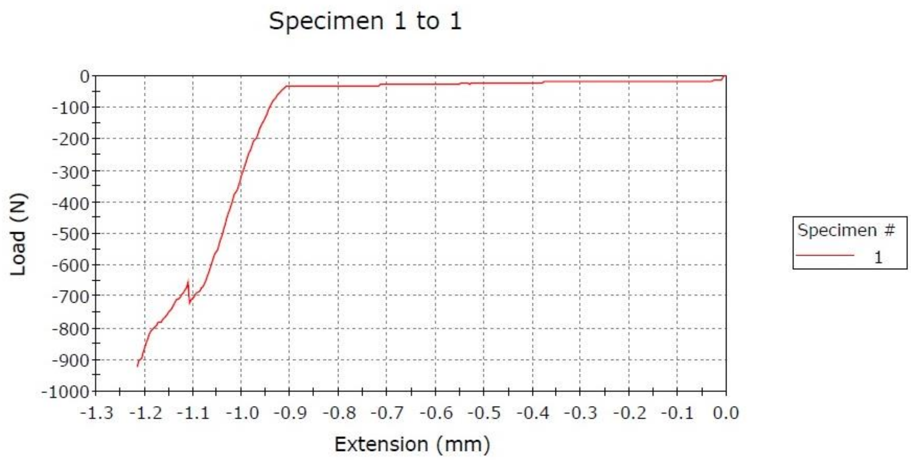
Figure 5.3 Graph shows the immediate fracture of all zirconia bridge

Table 5.1 Fracture behavior of the all zirconia bridges

All zirconia		
10 bridges	Premolar fracture (Retainer)	
1 bridge	Molar and Premolar fracture (Retainer)	
4 bridges	2 Molar and Premolar (Connector) 2 retainer (1 full molar and 1 part premolar)	
15 bridges		

Zirconia frameworks

The zirconia framework was the weakest between all the groups, the mean force being 898.4 N (min 651.0 N, max 1144.0 N, SD ± 132.5). Zirconia frameworks showed immediate fracture when force (N) was applied using the Instron machine (Figure 5.4) Out of the 15 zirconia frameworks five bridges showed fracture in the molar abutment coverage, two in the premolar abutment coverage, six in both the molar and premolar abutments and last two zirconia frameworks had fractures in the abutment molar connector (Table 5.2).



	Extension at Machine Break (mm)	Compressive stress at Yield (Zero Slope) (MPa)	Energy at Yield (Zero Slope) (J)
1	-----	-----	-----

	Load at Yield (Zero Slope) (N)	Load at Machine Break (N)	Load at Machine Peak Load (N)
1	-----	-----	-932.90000

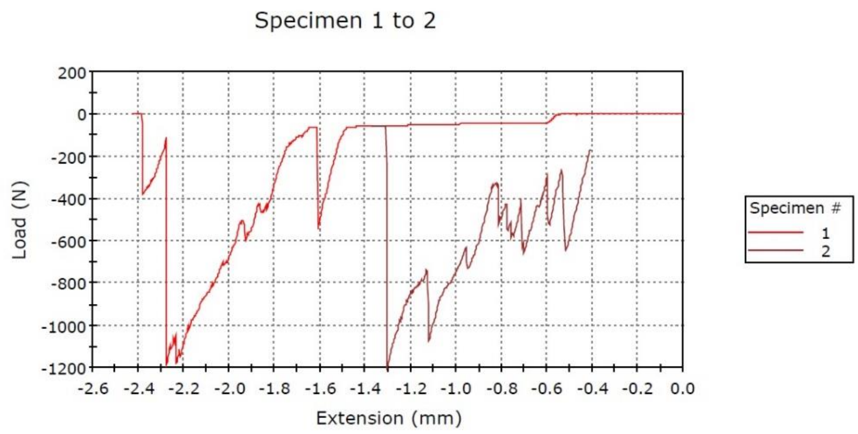
Figure 5.4 Graph shows force application (N) and immediate fracture of zirconia framework

Table 5.2 Fracture behavior of the zirconia frameworks

Zirconia framework		
5 bridges	Molar fracture	
2 bridges	Premolar fracture	
6 bridges	Molar and Premolar (Retainer)	
2 bridges	Molar (Connector)	
15 bridges		

Veneered zirconia bridges

This type of bridge was second place in force resistance, the mean force applied that led to the failure (fracture) of the bridges was 1235.3 N (min 715.0 N, max 1368.0 N, SD ± 243.6). The behaviour of failure differed from the all zirconia bridges due to the veneering layer on top of the zirconia framework. Nine of the veneered zirconia frameworks demonstrated two steps of deformation, the first being when the pressed veneering ceramic fractured and the second total failure was when the zirconia framework fractured (Figure 5.5), the remaining six veneered frameworks showed an immediate bridge (Veneering and zirconia) fracture without going from the first to the second deformation stages. Seven veneered frameworks out of 15 fractured at the premolar abutment coverage, five at the molar abutment coverage and three had both molar and premolar abutment coverage fractures (Table 5.3).



	Extension at Machine Break (mm)	Compressive stress at Yield (Zero Slope) (MPa)	Energy at Yield (Zero Slope) (J)
1	-1.61	0.25827	0.00205
2	-1.42	3.69913	0.04578

	Load at Yield (Zero Slope) (N)	Load at Machine Break (N)	Load at Machine Peak Load (N)
1	-45.64000	-550.30	-1188.00000
2	-653.69001	-1209.00	-1209.00000

Figure 5.5 Graph shows two steps fracture behavior in veneered zirconia frameworks

Table 5.3 Fracture behavior of the veneered zirconia bridges

Veneered zirconia framework		
7 bridges	Premolar fracture (Retainer)	
5 bridges	Molar fracture (Retainer)	
3 bridges	Molar and Premolar fracture (Retainer)	
15 bridges		

5.5 Discussion

In this laboratory study three types of zirconia-based restoration were fabricated (all-zirconia, zirconia framework and veneered zirconia frameworks) to fit ideally prepared teeth and provide a restoration with full anatomical features to simulate the clinical conditions, unlike some previous studies which have used metal cylinders (Sundh and Sjogren, 2004, Sundh et al., 2005, Kanat et al., 2014a) with no anatomic form and un-contoured zirconia blocks (Sundh and Sjogren, 2004). This is important as the irregularities encountered in a prepared tooth and a fully contoured restoration may impact upon the thickness of the materials at various sites within the restoration, produce areas of greater stress concentration especially at cusp tips and might influence crack propagation (Oh and Anusavice, 2002). As such, the results from this study may be considered to more closely represent the clinical situation. However there are some obvious differences compared to a study that perhaps was conducted *in situ*; prepared teeth would consist of dentine and a pulp with pain receptors and slung in a periodontal ligament which functions in a synergistic manner and acts as a shock absorber when force is applied on the tooth in the real clinical situation (Ho et al., 2004, Naveh et al., 2012). These are all factors that might account for differences between the results from this laboratory study and that from a clinical or *in situ* study. In theory an *in situ* study would be possible where teeth that are prepared for a bridge receive three bridges (as in this study) and the patient applies occlusal loading, measured with a strain gauge, until failure of the bridge. Not only would this be un-ethical due to the potential damage and harm to the patient it is unlikely that the patient would be able to apply the forces reached for failure in this study (see later in this discussion).

The three types of restoration investigated in this laboratory study were chosen, principally because the zirconia framework and all zirconia bridges had a different thickness, allowing investigation of the impact this would have on strength. In addition, it has been argued that veneering can influence the strength of the restoration and mode of failure which has been related to the thicknesses of the restoration core (metal and ceramic) and veneering ceramic together (Lund and Barber, 1992, Wakabayashi and Anusavice, 2000). The un-veneered and veneered zirconia frameworks therefore allowed investigation of the impact that ceramic veneering has on longer span three unit bridges.

A 0.5 mm thickness of zirconia is considered to be adequate for sufficient strength of zirconia to withstand normal occlusal forces and adequate for ceramic veneering (Sundh and Sjogren, 2004). The thickness of the zirconia frameworks can be altered in the CAD software, but more often than not the CAD CAM system default settings are used, which range from a uniform thickness of 0.5 mm to 0.8 mm. In the clinical situation, a heavier occlusal reduction in the area of a cusp tip for example, could, with a uniform coping thickness, lead to a thick layer of unsupported veneering ceramic which is inherently weak and this may account for some of the veneering ceramic failure that are seen clinically (Vult von Steyern et al., 2005, Larsson et al., 2007). In this study, whilst a uniform 0.7 mm thickness was used for the framework retainer, the problem of unsupported ceramic was avoided due to the ideal tooth preparation following the contours of the occlusal surface of the tooth and reducing the tooth occlusally by the recommended 1.5 – 2.0 mm (Blair et al., 2002). The standardised veneering process also ensured that the veneering ceramic on all veneered bridges were of an identical thickness.

Previous studies that have measured the load required to fracture all ceramic zirconia based restorations are detailed in Table 5.4, and surprisingly the results demonstrate a wide range, varying from as low as 346.0 N to as high as 6262.7 N (Tinschert et al., 2001a, Sundh and Sjogren, 2004, Sundh et al., 2005, Fischer et al., 2007, Aboushelib et al., 2008, Beuer et al., 2009f, Kanat et al., 2014a). This might be due to many factors such as the thickness of veneering ceramic, anatomical variation of the veneering ceramic, loading method (Aboushelib et al., 2008) the number of units, load application location and angulation. This makes it impossible to compare the forces from the different studies in Table 5.4. The forces recorded for failure in this laboratory study fell within the range of the previously published work (all zirconia 1858.5 N (min 1348.0 N, max 2968.0 N, SD ± 430.5), zirconia frameworks 898.4 N (min 651.0 N, max 1144.0 N, SD ± 132.5) and finally veneered zirconia frameworks 1235.3 N (min 715.0 N, max 1368.0 N, SD ± 243.6)) but this is unsurprising considering the range from the previously published literature.

Table 5.4 Studies showing the range of force required to fracture zirconia bridges

Study	Number of unites	Restoration type	Sample size	Force range (N)
(Tinschert et al., 2001a)	3-unit bridge (P-M)	Frameworks V.S. Veneered	2 0	IPS Empress (F) < 1000.0 In-Ceram Zirconia (V) ≥ 1000.0 DC-Zirkon (V) ≥ 2000.0
(Sundh and Sjogren, 2004)	Single unit (cylinder),	Veneered (Denzir) Default core V.S. 0.5 mm core	40	(V Eris) 4114.0 (default core) (V Eris) 2740.0 (0.5 mm core) (V Emp(II)) 3486.0 (default core) (V Emp(II)) 2226.0 (0.5 mm core)
(Sundh et al., 2005)	3-unit (cylinders)	Frameworks & veneered	20	(F) 3291.0 – 3480.0 (V Eris) 2237.0 – 2251.0 (V Vita D) 1611.0 - 1973.0
(Fischer et al., 2007)	Single unit (Metal canine)	Veneered (seven veneering ceramics)	70	Emax 818.0, Cerabien 836.0, Rondo 849.9, Lava 852.3, Zirox 855.2, Triceram 930.5 and VM9 935.2
(Aboushelib et al., 2008)	Single unit	Veneered (CAD-on)	18	CAD-on 442.8 Layering 346.0
(Zahran et al., 2008)	Single unit (Molar)	Veneered (VM9)	20	Layering 1459.0
(Beuer et al., 2009f)	Single unit (Molar)	Veneered (CAD-on)	45	CAD-on 6262.7 Layering 3700.4 Pressing 3523.7
(Kanat et al., 2014b)	Single unit (cylinder)	Veneered (CAD-on)	90	CAD-on 4408.0 Layering 4323.0 Pressing 2507.0

From all the studies that have investigated the strength of veneered zirconia restorations (Table 5.4) only two have looked at bridges (Tinschert et al., 2001a, Sundh et al., 2005) and in only one of these two studies was the strength of zirconia frameworks compared with the veneered bridge to directly look at the impact of veneering (Sundh et al., 2005). In this one study in which frameworks were compared with veneered frameworks (Sundh et al., 2005), it was surprising that frameworks showed significantly higher resistance to fracture prior to heat treatment and veneering. Although, the strength of the veneered zirconia was inferior to the zirconia frameworks, they still had high resistance to load approaching that of the all-zirconia bridges in this study. This was totally the opposite to the results of this laboratory study, which found that the strength of the framework and bridges improved significantly when the veneering ceramic had been added. This difference may be attributed to the fact that the zirconia in this study was milled in its pre-sintered state, and became stronger during subsequent firings, and in the study by Sundh et al., (2005) the frameworks were milled in a sintered state where further firings weakened the bridges.

The results from the second study are difficult to interpret as it did not compare like with like; the strength of two veneered zirconia frameworks (In-Ceram Zirconia and DC-Zirkon) were compared with that of un-veneered leucite reinforced porcelain frameworks (Tinschert et al., 2001a). The results showed that veneered zirconia had higher resistance to fracture loads compared with the leucite reinforced ceramic, and whilst interesting the comparison is not logical, because the frameworks are made with completely different materials with inherent differences in strengths and a comparison with veneered leucite frameworks was also not made. This study did not provide the reader with absolute fracture loads but instead gave readings above or below a certain threshold, but comparing the results with that of this study the results for the veneered zirconia (In-Ceram) frame works were broadly in agreement with that of this laboratory study.

The other studies in Table 5.4 investigated the strength of single unit veneered zirconia restorations only with none comparing the strength of the coping only with that of the veneered coping as in this study; the loads to failure ranged between 346.0 N and 6262.7 N. The wide variation in loads may be explained by the different types of veneering ceramics used, with all conventionally (layering technique) veneered restorations having a high resistance to fracture loads (818.0 N to 4114.0 N (Sundh and Sjogren, 2004, Fischer et al., 2007)), different thicknesses of zirconia core (Sundh and Sjogren, 2004), and different veneering techniques (CAD-on 442.8 N to 6262.7 N, layering 346.0 N to 4323.0 N and pressing 2507.0 N to 3523.7 N (Aboushelib et al., 2008, Beuer et al., 2009f, Kanat et al., 2014a)).

One study stands out as having significantly lower strength than the others and that obtained in this study (CAD-on 442.8 N and layering 346.0 N) (Aboushelib et al., 2008). In that study the CAD-on and layering techniques were compared and the reason for the lower strength are difficult to explain, other than fact that the fracture strength test used resin dies as a base for the investigated specimens and a sheet of tough rubber (0.5 mm) perhaps creating a greater wedging effect between cusps; what constitutes failure is also not clear.

It is interesting to note that the mean force required to fracture the veneered zirconia frameworks (1235.3 N) in this study, which were veneered using the pressing technique, was lower than that previously reported for single unit veneered restorations also veneered using the pressing technique (2507.0 N – 3523.7 N) (Beuer et al., 2009f, Kanat et al., 2014a). The difference is most likely to be due to the length of the span in the bridges compared to crowns where potential flexure of the bridge, at thinner sections such as the connector (or retainer) can lead to earlier failure (Larsson et al., 2007). In the third laboratory study of this thesis the effect that increasing the span of bridges from three unit to four unit had on internal and marginal fit was investigated, however the effect this would have on bridge strength was not investigated. This together with the connector diameter could indeed impact on the strength of the bridge and merits further work.

The results of this study (Figure 5.6) and the previous studies in Table 5.4, clearly show that all zirconia, zirconia frameworks and veneered zirconia bridges, with their variation in zirconia thickness, have a mean fracture load (2968.0 N, 898.4 N and 1235.3 N respectively) that is higher than the maximum bite force of 350 to 850 N that can be generated between posterior teeth (Bates et al., 1975, Gibbs et al., 1986) and 120 N to 350 N that can be generated between anterior teeth (Helkimo et al., 1977, Tortopidis et al., 1998). Clinical failures that are seen may therefore be more likely due to inappropriate design in the CAD software or flaws that occur in the veneering process.

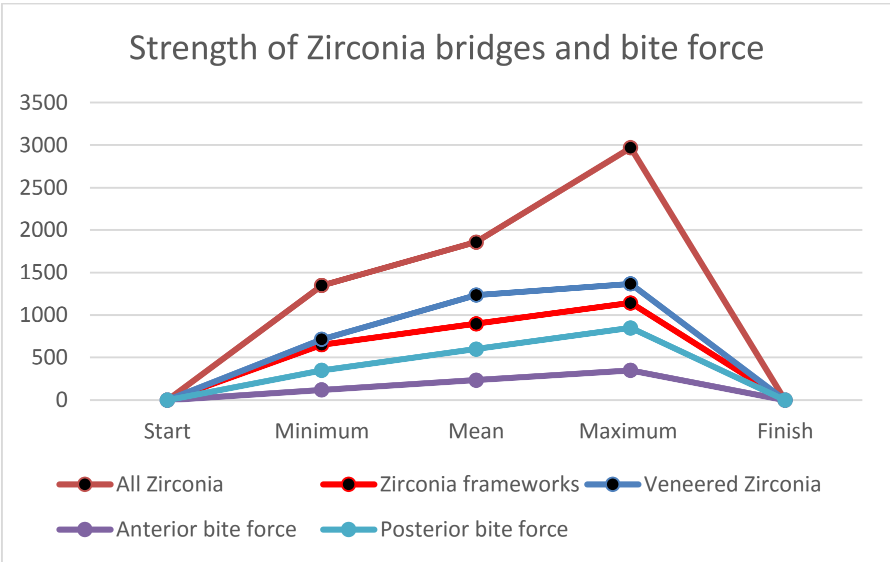


Figure 5.6 The strength (N) of three zirconia restoration bridges and maximum bite force

In addition to the bite force in the oral cavity, other factors can have an effect on the longevity of the restorations, such as humidity, acidity and temperature (Zhang and Chen, 2011). Artificial ageing could be performed by applying load cycles on zirconia based restorations of varying force under differing temperatures and humidity (Lameira et al., 2015). This was not done in this study as it was not the main aim but it is clear that this could have an impact clinically and is an area for future research where an artificial oral environment could be created including the use of teeth with dentine and periodontal ligament simulation and cyclic loading in more than just an axial direction (Qutieshat, 2016).

Catastrophic failure as in this study is not the only mode of failure, another problem encountered is smaller cracking or chipping of the veneering ceramics from the core material (Zhang et al., 2012). This may result from residual stress that can develop during the manufacturing process, which will lead to crack propagation under functional load and chipping of the veneering ceramic (Swain, 2009). It has been reported in a three year and five year follow-up study that chipping of ceramic from zirconia bridge frameworks reaches a prevalence of 13.0 % and 15.2 % respectively (Sailer et al., 2006, Sailer et al., 2007a). On the other hand metal ceramic restorations showed lower rates of veneering ceramic chipping (2.7 % to 5.5 %) over an observation period of 10 to 15 years (Valderhaug, 1991, Guess et al., 2008). Whilst the incidence of chipping is greater in the zirconia based restorations compared with metal ceramic restorations, such chipping may not lead to an un-aesthetic restoration; chipping of the veneering ceramic that happens with metal ceramic restorations will either show the opaque ceramic layer or the metallic core, for zirconia restorations the coping or framework is tooth coloured.

It has clearly been shown that CAD CAM systems can fabricate zirconia cores in relatively thin sections (0.5 mm to 0.8 mm) which can withstand high occlusal loads when veneered (Tinschert et al., 2001a, Sundh and Sjogren, 2004, Sundh et al., 2005, Zahran et al., 2008). Whilst this study has shown that the all zirconia bridges produced the highest fracture strength, even the thinner frameworks were able to withstand forces higher than occlusal forces achieved between anterior teeth. This raises the question, is it possible to minimally prepare anterior teeth for fully anatomical zirconia restorations with adequate aesthetics?

Advances and improvements in stains and techniques for zirconia can now lead to better aesthetics than was originally achieved and this therefore is a real possibility and needs further work.

5.6 Conclusion

Within the limitations in this study, the following conclusion scan be drawn:

1. Zirconia based restorations showed high resistance to vertical loads.

2. Veneering ceramic increased the strength of zirconia framework.

3. All the zirconia based restorations, including the thin section frameworks, can withstand occlusal loads.

Chapter 6

Laboratory study 5

Digital Impression versus Conventional impression

Laboratory study 5

Digital Impression versus Conventional impression

6.1 Introduction

Conventional impression techniques using an impression tray and impression material have been common practice for a many decades, aiming to produce a stone cast which transfers accurate information from the patient's mouth to the laboratory, and as such has been the gold standard (Henkel, 2007, Lee et al., 2015). Whilst widely used, it is important to follow several steps to produce an accurate dental impression, such as choosing the correct material and technique for the task in hand (Nissan et al., 2000, Chen et al., 2004, Levartovsky et al., 2014) This, in turn, will lead to an accurate dental stone cast and dental restoration (Hung et al., 1992, Maruo et al., 2007). Even by following all the appropriate steps and instruction it is still subjected to 'guesswork' in that once the impression is cast the stone model produced may not be fit for purpose, even though the impression subjectively looked satisfactory. In addition, conventional impressions may be uncomfortable for some patients (gag reflex) and the armamentarium can be expensive (Garg, 2008).

Since the 1950s elastomeric impression materials have been used routinely for indirect restorations (Christensen, 1997, Maruo et al., 2007) due to their high accuracy, dimensional stability, excellent elastic recovery, minimum permanent distortion and good tear strength (Bindra and Heath, 1997, Christensen, 1997, Mandikos, 1998, Brosky et al., 2002).

Since the introduction of dental CAD CAM as a technology that produces highly accurate and precise indirect restorations, there has been an increased need for an accurate, easy and less time consuming impression (Miyazaki et al., 2009). The first CAD CAM system (CEREC) that was introduced by W. Mörmann and M. Brandestini in the 1980s, had an intraoral scanner which picked up information (cavity/ tooth preparation) from the patient's tooth and relayed this to the CAD system (Mörmann et al., 1989). In this way the digital impression can eliminate some of the problems that occur with conventional impressions such as: improper impression tray selection, separation of the impression material from the tray, distortion of the impression material (due to disinfection or prolonged storage), infection control (disinfecting the impression), and, finally, compatibility of dental stone with the impression material (Christensen, 2009, Almortadi and Chadwick, 2010).

Today, there are many digital impression devices available commercially and the digital impression concept is rapidly growing with each new device having its own specification. This has made it important to compare digital impressions to conventional impressions, and to compare impressions obtained with different intraoral scanners.

6.2 Aims and objectives

The aim of this study was to compare the accuracy (internal and marginal) of fit of three unit bridges designed and manufactured using a CAD CAM system using information from a conventional impression technique (scanned stone models) and digital intra oral scan.

6.3 Material and Methods

Tooth preparation and Quality control

The ideally prepared and quality controlled tooth preparations used in the first laboratory study were also used in this study.

Digital Impression, conventional impression and all zirconia bridges manufacture

The digital file of the tooth preparations obtained in the first laboratory study was used to produce 30 identical non-sectioned Stereolithography models (SLA models, In'Tech Industries, Inc. USA). Each model was treated as an independent patient case and had a unique number to differentiate it from the other models. The 30 models (cases) were then randomly divided into two groups, 15 were assigned to a conventional silicone putty and wash impression technique and 15 were assigned to a digital impression (LAVA C.O.S).

Digital impression

Each of the 15 SLA models assigned to the digital impression group were scanned using the Lava C.O.S (3M ESPE, Seefeld, Germany) adopting the same steps that were used and described in the first laboratory study so creating 15 digital impression files, one for each independent case (no extra SLA models were ordered) (See the first laboratory study materials and methods).

Conventional impression

The conventional impressions were taken of the 15 remaining SLA models using a two phase (putty and wash), single stage impression technique using an addition cured silicone impression material (AFFINIS® putty soft, COLTENE, LOT NO. 38620 and AFFINIS®, Light body, COLTENE, LOT D54256) in a metallic sectional tray. The impressions were then poured up using type IV super hard stone (SHERAPREMIUM, LOT 41426, SHERA Werkstoff -Technologie GmbH & Co. KG.) to produce stone models (Figure 6.1) for each independent case (total 15 cases). The models were trimmed, sectioned and prepared for scanning using the laboratory scanner (Lava™ Scan ST optical scanning system). The silicon material was chosen because it is the conventional impression material of choice at Dundee Dental Hospital. To create the 3D virtual model from the on-site laboratory scan the same steps were used as for the digital impression (creating a new case, assigning the prepared and missing teeth and designing the restoration as described in the first laboratory study), the only difference being the scanning method. The on-site laboratory scanner was a non-contact, optical scanner with fringe projection triangulation for high accuracy.

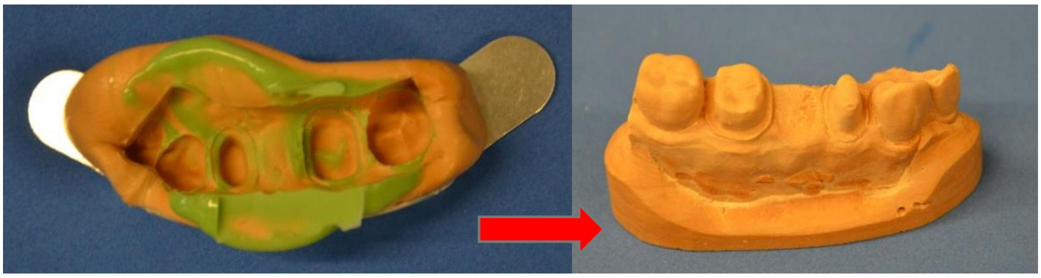


Figure 6.1 Silicone impression in sectional metallic tray used to produce a type IV Stone model

Bridge design and fabrication

The data captured for each model (15 SLA models and 15 stone models obtained from the conventional silicone impressions) were used to design the corresponding all zirconia bridges in the CAD system. The same settings were used for both types of impression capture to ensure that the bridges were identical from a production point of view, with the only difference being the impression and scanning method (die spacer 0.095 mm extra vertical (occlusal), 0.075 mm extra horizontal (buccal, mesial, distal and lingual) and minimum coping thickness 0.5 mm). This process allowed the manufacture of 30 three unit all zirconia bridges for the corresponding independent case using a five axis CAM milling machine (Lava™ CNC 500 Milling System, 3M ESPE) and dry milling process. Semi-sintered zirconia multi blocks were used to fabricate the all zirconia FPDs (3M ESPE, Seefeld, Germany, LOT No. 470281, LOT No. 472678 and LOT No. 472678). The semi-sintered all zirconia bridges were placed in a custom furnace (Lava™ furnace 200, (3M ESPE, Seefeld, Germany) to fully sinter the zirconia framework at 1500°C for 4 hours 48 minutes (LAVA 1500, Non-shaded).

Restoration cementation

The 30 bridges from both groups were cemented permanently to their designated models. The force application device was used to cement the 30 bridges (cementation force = 30.0 N), using the same steps that were developed and adopted in the second laboratory study (See laboratory study two). RelyX™ Unicem 2 Clicker™ (3M ESPE, Seefeld, Germany, LOT No. 517676) self-adhesive Universal Resin Cement was used as the luting cement as described in the second laboratory study.

Preparation for, and SEM observation

The same preparation for sectioning and SEM technique used in the second laboratory study was used in this study for analysis of the internal and marginal fit of the dental restorations made using the two impression technique.

Statistical analysis

The internal and marginal cement gaps were recorded (pooled data from both abutment retainers - premolar and molar) for the all zirconia bridges manufactured from each impression technique. One way ANOVA was used to assess whether there were any statistically significant differences in the internal and marginal fits of the bridges produced using the two impression techniques. A t-test was used to compare the internal and marginal fit of the two abutment - retainers types (pre-molar and molar) to assess if there was any significant difference between the abutment – retainer types of the bridges made using the same impression method and between the abutment – retainer type from the different impression methods (IBM® SPSS® 21).

6.4 Results

Internal fit

The mean internal fit for the all zirconia bridges made using the conventional impression was 98.6 µm (min 90.0 µm, max 120.0 µm and SD ± 7.2) and for the all zirconia bridges made using the digital impression it was 88.6 µm (min 80.0 µm, max 109.0 µm and SD ± 6.9). One way

ANOVA was used to compare the internal fit and to check if there was any significant difference between the two types of impressions. The result showed that there was a significant difference between the bridges made from the two impression techniques ($p = 0.00$). The bridges made using the conventional impression showed a greater internal gap (Figure 6.2).

Molar abutment-retainer and premolar abutment-retainer

The molar abutment-retainer fit was compared with the premolar abutment-retainers for the bridges made using the same impression (Conventional or Digital). In addition the molar abutment-retainer fit of the bridges made from the two impression techniques were compared as was the premolar abutment-retainers to determine whether there was any statistical significant different between the two impression techniques for one abutment tooth type using the t test.

Conventional impression technique

For the bridges made using the conventional impression technique the mean value of the internal fit of the molar abutment-retainers was 98.6 µm (min 91.0 µm, max 119.0 µm and SD ± 7.2) and for the premolar the mean was 98.5 µm (min 92.0 µm, max 119.0 µm and SD ± 7.1). No statistically significant difference was found in relation to both premolar and molar abutment - retainers internal fit when a conventional impression was taken (one way ANOVA, $p = 0.3$).

Digital impression technique

For the bridges made using the digital impression the mean value of the internal fit of the molar abutment-retainer was 88.6 µm (min 82.0 µm, max 109.0 µm and SD ± 6.1) and the premolar abutment-retainer the mean value was 88.6 µm (min 80.0 µm, max 109.0 µm and SD ± 6.9). There was no statistically significant difference found in relation to both premolar and molar abutment-retainers internal fit when a digital impression was taken (one way ANOVA, $p = 0.3$).

Conventional versus Digital abutment - retainers

A t-test was applied to the internal fit of the molar abutment - retainers of the bridges obtained from the two different impression techniques, the results indicated that there was a statistically significant difference ($p \leq 0.05$). Similarly the results obtained for the internal fit of the premolar abutment-retainers for the bridges obtained from the two different types of impression techniques indicated a statistically significant difference ($p \leq 0.05$) with the fit being closer for the bridges obtained from the digital impression.

Marginal fit

The mean marginal fit of the all zirconia bridges that were made using the conventional impression was 37.9 µm (min 36.0 µm, max 40.0 µm and SD ± 0.7) and for the digital impression restoration it was 28.2 µm (min 26.0 µm, max 29.0 µm and SD ± 0.7). One way ANOVA showed that there was a significant difference between the bridges made using the two types of impressions ($p \leq 0.05$). The results showed that the bridges made using the conventional impression technique had greater marginal gap (Figure 6.2).

Molar abutment-retainer and premolar abutment-retainer

The same comparisons that were made for the internal fit measurements were applied to the marginal fit measurements using One-way ANOVA, namely the molar abutment-retainers fit and premolar abutment-retainers fit for the bridges made using the same impression technique and from the different types of impression techniques were compared.

Conventional impression technique

For the bridges made using the conventional impression technique the mean value of the marginal fit of the molar abutment-retainers was 37.9 µm (min 37.0 µm, max 40.0 µm and SD ± 0.8) and for the premolar the mean was 37.8 µm (min 37.0 µm, max 39.0 µm and SD ± 0.7). One-way ANOVA results showed that there was no statistically significant difference between the molar and premolar abutment-retainers ($p = 0.4$).

Digital impression technique

For the bridges made using the digital impression, the mean value of marginal fit of the molar abutment - retainer was 28.2 µm (min 27.0 µm, max 29.0 µm and SD ± 0.7) and the premolar the mean value was 28.1 µm (min 27.0 µm, max 29.0 µm and SD ± 0.7). One-way ANOVA results showed that there was no statistically significant difference ($p = 0.3$) between the marginal fit of the premolar and molar abutment-retainers made using the digital impression technique.

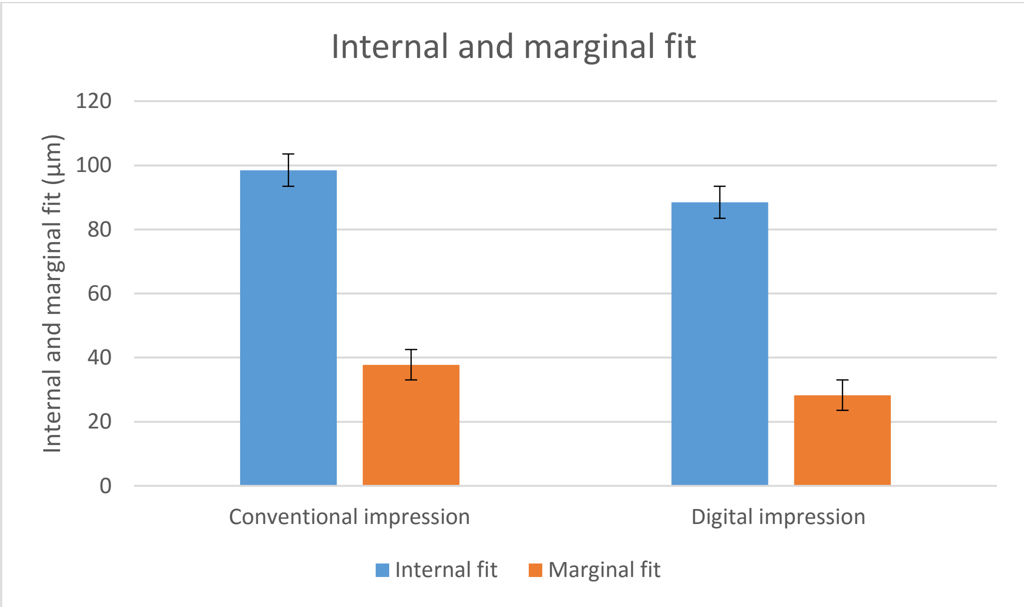


Figure 6.2 Mean fit (internal in blue and marginal in red) of the bridges made using the two types of impression technique (Conventional and Digital).

Conventional VS digital abutment retainers

One way ANOVA was applied to the molar abutment - retainer mean results of the bridges obtained from the two different impression techniques. The results showed that there was a statistically significant difference ($p \leq 0.05$) between the marginal fit of the molar abutment-retainer made from the two different impression methods (Conventional and Digital). The marginal fit results obtained for the premolar abutment-retainer from the two different types of impression techniques showed that there was a statistically significant difference between the two retainers ($p \leq 0.05$)), with the conventional impression in both cases resulting in greater marginal gaps.

6.5 Discussion

Conventional impressions can be affected by many clinical factors such as, impression technique, impression material, finish-line location, saliva flow, patients mouth opening (accessibility) and periodontal condition (Syrek et al., 2010). Some of these factors can also affect intraoral scanning, and hence can have an impact on the final impression (conventional or digital) which will affect the fit of the final restoration. Therefore, this laboratory study compared silicone based conventional impression with digital impression (intraoral scanner) under ideal conditions, to investigate whether the impression technique could impact upon the internal and marginal fit of three unit all zirconia bridges. The previously mentioned confounding clinical factors are not applicable for this laboratory study, thus reducing the number of variables that could have an effect on the impression (digital and conventional) of the three unit all zirconia bridges, leaving the impression technique as the only variable.

The conventional impression material used in this study was a silicone-based impression material, because they are the most widely used in dentistry and for the material properties outlined in the introduction (Vitti et al., 2013) namely high accuracy, dimensional stability, excellent elastic recovery, minimum permanent distortion and good tear strength (Bindra and Heath, 1997, Christensen, 1997, Mandikos, 1998, Brosky et al., 2002). The conventional impressions were made using a sectional metallic tray which ensured more rigidity and support to the impression material during impression taking and stone model pouring. This is important as tray selection and rigidity of the tray could have had an influence on the accuracy of the impression which will affect the final restoration (Hoyos and Soderholm, 2011). As such the conventional impressions were optimal. Despite this, the results of this laboratory study showed a statistically significant difference between the two techniques, with the digital impressions producing restorations with better internal and marginal fit (88.6 µm, 28.2 µm respectively) compared to the conventional impression (98.6 µm, 37.6 µm respectively). However, both techniques resulted in restorations with fit within the range that is thought to be clinically acceptable (McLean and von Fraunhofer, 1971, Martinez-Rus et al., 2011).

The results obtained from this laboratory study are in agreement with studies published since the conception of this study (2011), which compared conventional impressions with digital impressions (Table 6.1).

Table 6.1 Studies comparing digital impressions and conventional impressions, digital (D) and conventional (C) in relation to marginal fit.

Study	Model	Digital / Conventional Results for Marginal Fit (mean)	Measurment	Comments
(Henkel, 2007)	Patients Crown	iTero / conventional	Questionaire	Digital impression is promising and the technology will rapidly increase
(Syrek et al., 2010)	Patients Crown	Lava COS / conventional (2 step silicone) (D) 49.0 µm / (C) 71.0 µm	Impression/ Microscope	Digital superior to conventional
(van der Meer et al., 2012)	Model Implant	CEREC, iTERO, Lava	Rapid form software	Lava had the best precision
(Seelbach et al., 2013)	Model Crown	CEREC, Lava, iTero & conventional (Silicone) 1 & 2 step ((D) 88.0 µm, 29.0 µm, 50.0 µm, (C) 35.0-56.0 µm, respectively)	Microscope	Digital and conventional are both accurate
(Guth et al., 2013)	Model Crown	Lava/ conventional (polyether) (D)17.0 µm and (C) 23.0 - 36.0 µm	Inspection Software	Digital superior to conventional
(Lee and Gallucci, 2013)	Model	iTero/ conventional (silicone)	Questionnaire	Digital superior to conventional

	Crown	Ease (D) 30.4, (C) 43.1 Time (Mins) (D) 12:29, (C) 24:42		
(Ender and Mehl, 2013)	Model Crown	CEREC/ conventional (silicone) Precision (D) 20.4 µm and (C) 12.5 µm	Mircoscope	Conventional more precision than digital impression (full arch)
(Grunheid et al., 2014)	Patients	Lava /Conventional	Questionnaire	Conventional faster and reqiers less time (full arch)
(Yuzbasioglu et al., 2014)	Patients Crown	CEREC/ conventional (polyether) Time(Mins) (D) 4.1 and (C) 10.1	Questionnaire	Digital is easier than conventional
(Nedelcu and Persson, 2014)	Model	Lava,CEREC,iTero & E4D	3D compare software	Sig. diff between powder and non powder IOS
(Almeida e Silva et al., 2014)	Model 4 unit bridge	Lava/ conventional (polyether) (D) 63.9 µm and (C) 65.3 µm	Mircoscope	Digital superior to conventional
(Svanborg et al., 2014)	Models 3 unit bridge	iTero/ conventional (Silicone) (D) 44.0 µm and (C) 69.0 µm	3D software	Digital superior to conventional
(Ng et al., 2014)	Model Crown	3Shape/ conventional (silicone) (D) 48.0 µm and (C) 74.0 µm	Microscope	Digital superior to conventional
(Ueda et al., 2015)	Models	Lava/ conventional (polyether)	Microscope	Digital superior to conventional

	4 unit bridge	(D) 51.5 µm and (C) 72.9 µm		
(Pradies et al., 2015)	Patients Crown	Lava/ conventional (Silicone) (D) 76.3 µm and (C) 91.5 µm	Steremicroscope	Digital superior to conventional

The studies in Table 6.1 have investigated the accuracy of intraoral scanners, either by comparing different makes of intraoral scanners (van der Meer et al., 2012, Nedelcu and Persson, 2014), or by comparing one or more intraoral scanners with conventional impression (Henkel, 2007, Syrek et al., 2010, Guth et al., 2013, Lee and Gallucci, 2013, Ender and Mehl, 2013, Seelbach et al., 2013, Yuzbasioglu et al., 2014, Almeida e Silva et al., 2014, Svanborg et al., 2014, Ng et al., 2014, Ueda et al., 2015, Pradies et al., 2015). All but one of the previous studies are in agreement with the results from this laboratory study, concluding that digital impression is considered superior to conventional impression.

From all the studies in Table 6.1, only two studies concluded that a conventional impression is superior to a digital impression when used for full arch impressions (Ender and Mehl, 2013, Grunheid et al., 2014). There may be a number of reasons for this, for example are: un-experienced operator in using the intraoral scanner, measurement method and/or span length. It should be noted that these are the only studies where full arch impressions were investigated and it is recognised clinically that taking an accurate full arch conventional impression is demanding as it is done in one step and the impression tray has to be seated before the impression material starts to set. Whilst this is true, in the laboratory at room temperature, greater time is available for accurate working and access is unimpeded as it would be intra-orally with tongue and soft tissues etc. This may together with operator familiarity with the technique, explain the superior accuracy of the conventional impression (Ender and Mehl, 2013, Grunheid et al., 2014).

For the digital impression, on the other hand, the wand travels over the arch at a fixed distance from the teeth in all directions (labial, palatal, anterior and posterior). Using a laboratory model also facilitates this technique but unfamiliarity with the technique together with the distance the wand has to travel over (causing operator fatigue and poor stability) may explain why in the study by Ender and Mehl (2013) the digital impression was inferior. The difference in accuracy was greatest posteriorly, reaching a difference of around 170.0 µm, supporting the latter suppositions.

Single crowns were the most commonly investigated restoration in the previous studies, except for the study by van der Meer et al., (2012) who investigated the precision of digital impressions on dental implants (van der Meer et al., 2012), and three studies that investigated digital impressions and conventional impressions for multiple unit bridges (three and four unit bridges) (Svanborg et al., 2014, Almeida e Silva et al., 2014, Ueda et al., 2015). Concentrating on the results from the studies on bridges for comparison with the results from this study, the mean marginal fit obtained from the three studies for the digital impression ranged from 44.0 µm – 63.9 µm and for the conventional impression mean results ranged between 65.3 µm - 72.9 µm. The mean results for marginal fit in this laboratory study (digital impressions 28.2 µm conventional impression 37.6 µm) were superior (better fit) despite the fact that two of the previous studies also used the Lava system on similar span bridges. The difference may actually be down to the way in which the marginal gap was measured with two using a replica impression technique and microscope, which may not be as accurate as sectioning and investigation with the SEM as in this study.

Seelbach et al (2013), investigated the difference between three types of digital intraoral scanner (CEREC, iTero and Lava) with two techniques to obtain a conventional impression (single step and two step). The mean results for internal and marginal fit for each group were as follows, CEREC 88.0 µm and 30.0 µm respectively, Lava COS 29.0 µm and 48.0 µm, iTero 50.0 µm and 41.0 µm, single step conventional impression (Lava zirconia, Cera E) 36.0 µm, 44.0 µm and 33.0 µm, 38.0 µm respectively and, finally, the two-step conventional impression (Lava zirconia, Cera E) 35.0 µm, 56.0 µm and 60.0 µm, 68.0 µm respectively, it was concluded that the digital impression and conventional impressions (single and two step) all resulted in zirconia restorations with an acceptable fit, and that the Lava system resulted in the best fit of zirconia restorations for both digital and conventional impression techniques (Seelbach et al., 2013). It is interesting to note that the result from this study are very similar to those obtained for crowns made with the CEREC machine in the Seelbach et al. study (Seelbach et al., 2013). For both the iTero and CEREC crowns in the Seelbach study and the Lava bridges in this study the internal fit is higher than the marginal fit as this is generally what would be expected with the default settings on the CAD CAM machines, or even when these are customised as one would want the marginal gap to be as small as possible. It is therefore unusual to find that the Lava crowns in the Seelbach study had a marginal gap higher than that of the internal fit, which is the reverse to that found in this study. This is difficult to explain and unclear in the publication, but may be due to the technician/researcher altering the default settings in such a way or due to the fact that the marginal gap was not measured at the true periphery or external margin of the restoration.

It is often debated as to which technique, conventional or digital impression, is easier and user friendly for both the dentist and the patient. As a result this has been the focus of two papers by Lee and Gallucci, 2013 and Lee et al. (2013) (Lee and Gallucci, 2013, Lee et al., 2013b) in which both types of impression were taken for a single implant model. In the former study only dental students' views were evaluated using Visual Analogue Scales (VAS) and the overall time to take the impression and any additional time for retakes were evaluated. Time is obviously an important factor because it can be stressful for both the dentist and the patient while waiting for the material to set, in the anticipation of an acceptable outcome, and there is always the fear of a retch reflex (Akarslan and Yildirim Bicer, 2013). Time was investigated during the clinical procedure and evaluated through a questionnaire for both impression techniques in the study by Lee and Gallucci (2013). It was concluded that the digital impression required half the time (12.29 mins) compared to the conventional impression for total treatment (impression preparation time, working, impression/scan and retake). Most of the dental students in this study preferred the digital impressions over the conventional impression (Lee and Gallucci, 2013).

In the second study by Lee et al., (2013) the views (evaluated by questionnaire and VAS) of both dental students and experienced practitioners were compared following experience with both techniques. The students preferred the digital impression and considered it to be easier than the conventional impression, whereas the experienced dentists found the conventional impression easier. These results are what would be expected as the younger students may be more technologically minded and used to using similar equipment or gadgets and the experienced dentist may have developed a high level of skill using a more traditional approach. Despite this, both groups agreed on the level of difficulty of the digital impression and both experienced dentists and students agreed on the level of acceptability of both methods for future use (Lee et al., 2013b).

Where patient satisfaction and time are concerned, two studies are available in the literature and the opinion is divided and contradictory (Yuzbasioglu et al., 2014, Grunheid et al., 2014). Yuzbasioglu et al., (2014), investigated patient preference and treatment comfort of digital and conventional impression techniques, the time was recorded for each technique to be compared at the end of the study. In this study a questionnaire was used after each impression technique. The results showed high preference of the digital impression technique over the conventional technique and considered them more comfortable. Regarding the time recorded, digital impression showed better time efficiency compared with the conventional impression technique (Yuzbasioglu et al., 2014). Contrary to the first study, Grunheid et al, (2014), investigated full arch imprisoning using conventional and digital impression techniques for orthodontic patients, the results indicating that patients preferred the conventional impression and considered it to be faster and therefore, conventional impression required shorter time than that for the digital impression (Grunheid et al., 2014). The results of the two previous studies indicated that there is no consensus which makes it a good field for future investigations.

Another question that is always raised when digital intraoral scanners are mentioned is the effect of the powder 'coating layer', which is used with some systems such as 3M Lava COS and CEREC AC/Bluecam. In 2014 Nedelcu and Persson, investigated four different types of intraoral scanners from which two required powder (3M Lava COS and CEREC AC/Bluecam), and two did not (iTero and E4D). They compared the four systems and investigated the effect of excessive coating on the scanning accuracy by comparing the accuracy of the scans only with that produced by a gold standard laboratory scanner (ATOS II SO, software v7.0; GOM). A significant difference was found between the non-coating and coating systems with the coating systems producing more accurate scans compared with the non-coating systems. They also found that excessive coating did not have any negative effect on the scan (Nedelcu and Persson, 2014).

6.6 Conclusion

Within the limitation of this study, the following conclusions can be drawn:

1. The digital impressions showed better fit compared to the convnetional impressions with a difference of approximately 10.0 µm for both internal and marginal fits.
2. Digital impressions required less armementarium compared to conventional impresson, although, technology needed to produce the digital scan is currently very expansive.
3. Both digital and conventional impression techniques can produce clinically acceptable bridges.

Chapter 7

Audit

Dentist, technician and patient satisfaction of dental restorations made from CAD CAM zirconia based restorations and economic evaluation (cost analysis)

Dentist, technician and patient satisfaction of dental restorations made from CAD CAM zirconia based restorations and economic evaluation (cost analysis)

7.1 Introduction

As improvements in CAD CAM and ceramic technology have taken place to combine strength and optimal aesthetics there has been a concomitant increase in demand for such restorations (Blair et al., 2002, Komine et al., 2010). In addition there has been an associated increase in research in this field over the 5 years since this PhD project commenced.

Whilst much work has been done on strength, fit, and survival of zirconia restorations (Abduo et al., 2010) this has mainly been done on single unit restorations with much less on multiple unit restorations. Only a modest amount of work has been carried out on dentist satisfaction and acceptance of digital and conventional impressions (Lee and Gallucci, 2013, Lee et al., 2013b). There has been even less on patient satisfaction and that which has been done has only investigated satisfaction with survival and longevity at follow up appointments (Kan et al., 2003, Gotfredsen, 2004, Meijndert et al., 2007, De Rouck et al., 2008, Tartaglia et al., 2011, Shi et al., 2015). No work has been carried out to determine patient satisfaction with the completed restoration at the fit appointment. Similarly no known work has been carried out in relation to technician satisfaction with the clinical work related to CAD CAM and zirconia based restorations; most surveys of dental technicians that have been published have evaluated job satisfaction, continual professional development (CPD) and remuneration (Bower et al., 2004, Marachlioglou et al., 2010, Ross et al., 2012).

Whilst an important factor in business, cost analysis is an insignificantly important subject in medicine and dentistry. However in an era of greater accountability such analyses are becoming an important aspect of health care and yet there is relatively little in the literature in relation to this (Joda and Bragger, 2015). It is assumed that cost analysis might be an interesting information for health care providers, patients and insurance companies (Walton and Layton, 2012). In the literature, few studies investigating cost effectiveness are available and those that have been carried out have compared the cost between different restorations, for example comparing single unit implant crowns with three unit bridges (Bragger et al., 2005, Bouchard et al., 2009), or where edentulous patients are concerned, comparing various types of removable prostheses (Attard et al., 2005, Zitzmann et al., 2005). None of these studies have investigated the cost of materials or equipment involved in the fabrication of such restorations.

7.2 Aim of the Audit /Questionnaire

The first aim of this study was to evaluate the satisfaction rate of the dental team (dentist and dental technician) and patients with regard to dental restorations made using zirconia milled by CAD CAM. The second aim of this study was to compare the cost of these restorations with metal ceramic restorations made from high fusing gold alloys.

7.3 Material and methods

Four questionnaires were designed to be distributed with consecutive zirconia dental restorations made using CAD CAM at Dundee Dental Hospital and School. The questionnaires were piloted among the targeted population (five per questionnaire) before being finalized, to maximize the clarity. Once the final questionnaires were ready, copies were sent to obtain Caldicott Guardian approval (NHS Tayside Information Governance Manager, Ref Caldicott/CSAppNA080711 in 08-July-2011, (Appendix 1)).

The four questionnaires were kept in the onsite laboratory and at the initial preparation appointment were collected by the dentist. Each set of questionnaires were coded with the same unique numeric code to ensure confidentiality and anonymity of the patients.

The first questionnaire was for the dentist to complete at the end of the tooth preparation appointment. It consisted of 12 questions which mainly concentrated on the teeth and supporting tissues, when tooth preparation was completed, type of restoration required, occlusal registration and impression technique used (Figure7.1).

DENTIST QUESTIONNAIRE (AT PREPARATION) 1

DATE / / 20	PATIENT CODE	UNDER-GRAD ◯ POST-GRAD ◯ CONSULTANT ◯ NON-CONSULTANT STAFF: FOUNDATION ◯ SPR ◯ SHO ◯ OTHER:
NEW PREPRATION ◯ REPLACMENT RESTORATION ◯	**TEETH** **8 7 6 5 4 3 2 1** **8 7 6 5 4 3 2 1**	SINGLE UNIT CROWN ◯ BRIDGE ◯ Implant ◯ Inlay/Onlay ◯
TECHNICIAN CODE	**SHADE** SELECTED BY TECHNICIAN	**(DISSATISFIED)** **(VERY SATISFIED)** **DENTIST TO MARK ON SCALE WITH A VERTICAL LINE HOW SATISFIED WITH THE SELECTED SHADE.**

GINGIVAL CONDITION

POOR ◯ ACCEPTABLE ◯ EXCELLENT ◯

PREPARATION (FINISH-LINE)

SHOULDER ◯ CHAMFER ◯ DEEP CHAMFER ◯ BEVELLED SHOULDER ◯ KNIFE EDGE ◯

PREPARATION (FINISH-LINE AT DEEPEST ASPECT)

SUPRA-GINGIVAL ◯ SUB-GINGIVAL ◯ AT GINGIVAL LINE ◯

CORE MATERIAL

AMALGAM ◯ COMPOSITE ◯ GI/RMGI ◯ TOOTH ◯ METAL ◯

MORE THAN ONE CYCLE CAN BE TICKED.

IMPRESSION MATERIAL USED FOR PREPARED TEETH:

……………………………………………………………………..

FACE-BOW

YES ◯ **NO** ◯

OCCLUSAL RECORD

YES ◯ **NO**◯

IF YES: WAX ◯ **SILICONE REG. PASTE** ◯ **MARKED INDEX TEETH** ◯

COMMENTS:

MARK LEVEL OF SATISFACTION ON SCALE FROM DISSATISFIED TO VERY SATISFIED, PLEASE COMMENT IF DISSATISFIED.

Figure 7.1 Dentist questionnaire (at preparation)

The second questionnaire was given to the laboratory technician to complete which concentrated on the quality of impression, tooth preparation, occlusal clearance and occlusal record (Figure7.2).

TECHNICIAN QUESTIONNAIRE (TECHNICAL) 2

MARK LEVEL OF SATISFACTION ON SCALE FROM DISSATISFIED TO VERY SATISFIED, PLEASE COMMENT IF DISSATISFIED.

DATE / / 20	TECHNICIAN CODE	PATIENT CODE	TIME NEEDED ON CAD
IMPRESSION (QUALITY FOR CASTING) **(DISSATISFIED)** … **(VERY SATISFIED)** **COMMENTS:**			
TOOTH PREPARATION (QUALITY FOR SCANNING) **(DISSATISFIED)** … **(VERY SATISFIED)** **COMMENTS:**			
OCCLUSAL CLEARANCE **(DISSATISFIED)** … **(VERY SATISFIED)** **COMMENTS:**			
OCCLUSAL RECORD **(DISSATISFIED)** … **(VERY SATISFIED)** **COMMENTS:**			
OVERALL **(DISSATISFIED)** … **(VERY SATISFIED)** **COMMENTS:**			
COMMENTS:			

Figure 7.2 Technician questionnaire

The third questionnaire was completed by the dentist at the fit appointment, it concentrated on the quality of the zirconia restoration in relation to the appearance, shade, shape, occlusion, marginal fit and contact point (Figure 7.3).

Finally, the fourth questionnaire was handed to the patient to complete in the waiting room and this concentrated on their restoration in relation to the appearance, colour match, shape and occlusion (Figure 7.4).

In the questionnaires ten point Likert scales, (bipolar scaling method, measuring either graded positive or negative responses to a statement), were used to measure the satisfaction rate of the dentists, technicians and patients.

Each series of questionnaires were assigned a unique code, so that the series could be collected anonymously after it was completed by the dentist (at preparation and at fit), technician and patient and re-united as a series.

DENTIST QUESTIONNAIRE (AT FIT) 3

MARK LEVEL OF SATISFACTION ON SCALE FROM VERY DISSATISFIED TO VERY SATISFIED, PLEASE COMMENT IF DISSATISFIED.

DATE / / 20	CASE CODE 1	UNDER-GRAD ◯ POST-GRAD ◯ CONSULTANT ◯ NON-CONSULTANT STAFF: FOUNDATION ◯ SPR ◯ SHO ◯ OTHER:
NEW PREPRATION ◯ REPLACMENT RESTORATION ◯	**TEETH** **8 7 6 5 4 3 2 1** **8 7 6 5 4 3 2 1**	SINGLE UNIT CROWN ◯ BRIDGE ◯ Implant ◯ Inlay/Onlay ◯

APPEARANCE

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

SHADE MATCH

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

SHAPE AND CONTOUR

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

OCCLUSION (AT TRY-IN)

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

OCCLUSION (AFTER ADJUSTMENT AND CEMENTATION)

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

MARGINAL FIT

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

CONTACT POINT

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

OVERALL

(VERY DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

Figure 7.3 Dentist questionnaire (at fit)

PATIENT QUESTIONNAIRE 4

MARK LEVEL OF SATISFACTION ON SCALE FROM DISSATISFIED TO VERY SATISFIED, PLEASE COMMENT IF DISSATISFIED.

DATE / / 20 AGE	GENDER MALE ◯ FEMALE ◯	PATIENT CODE

APPEARANCE

(DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

COLOUR MATCH

(DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

SHAPE AND CONTOUR

(DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

BITE AND COMFORT (AFTER ADJUSTMENT AND CEMENTATION)

(DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

OVERALL

(DISSATISFIED) **(VERY SATISFIED)**

COMMENTS:

COMMENTS:

PLEASE RETURN TO RECPTION.

Figure 7.4 Patient questionnaire

Economical evaluation

In order to evaluate the impact of cost on manufacture of indirect restorations the cost of gold and zirconia blocks needed for a defined number of units was calculated and compared. A unit in terms of indirect restoration was regarded as either a crown, inlay/onlay, bridge retainer or pontic.

As gold prices are fluctuant, this makes it difficult to determine the exact cost of dental restoration made out of gold. By searching the prices of gold between the years 2011 and 2015, the minimum price was £20/g and the highest was £37/g (http://goldprice.org/). In order to calculate the average cost of gold per unit of indirect restoration, data was collected from Dundee Dental Hospital and School restorative laboratory regarding the amount of gold (g) used to construct different indirect dental restorations (single, two units, three units, four units, and five units) from 2010 to 2014 log books. Indirect units can be made from zirconia blocks of different dimensions and costs. Depending on the size block used will depend on how many units can be milled from the block. For each block size the cost per unit generated was calculated based upon the cost of zirconia blocks in 2015. Hence the cost of each unit of indirect restoration prepared using high fusing gold alloy and zirconia blocks could be compared.

7.4 Results

Response rate

A total number of 75 sets of questionnaires were issued to dentists (at preparation and fit), technicians, and patients. The response rate varied from 58 (77.0 %) from the patients to 75 (100.0 %) from the technicians (Figure 7.5).

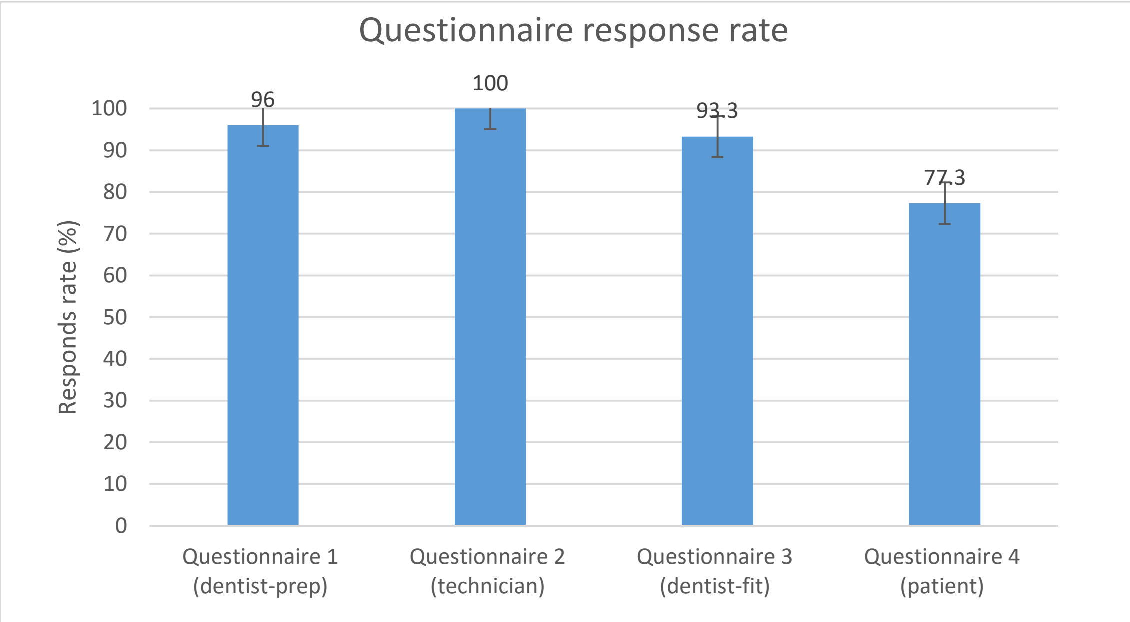


Figure 7.5 Questionnaire response (return) rate

Questionnaire 1 (Dentist at preparation)

The dentist preparation questionnaire (72, 96.0 % returned) included mainly factual and general questions. The responses are shown in (Figure 7.6). The responses were from 29 (40.0 %) under-graduate dental students, 7 (10.0 %) post-graduate dental students, 24 (33.0 %) consultants, 6 (8.0 %) non-consultant staff (foundation trainees) and 6 (8.0 %) speciality trainees. In total, the results from the questionnaires indicated that 127 teeth were prepared for indirect restorations, the majority of cases were new preparations (n = 40, 55.5 %), 28 (38.8 %) were replacement restorations and finally 4 (5.7 %) were combined between new preparation and replacement restoration. The majority of the questionnaires returned related to single crowns 56 (70.0 %), followed by bridges 16 (20.0 %), 1 (1.2 %) implant, and finally 7 (8.8 %) inlay and onlay, some responses had a combination of dental restorations (Figure 7.6).

DENTIST QUESTIONNAIRE (AT PREPARATION) 1

MARK LEVEL OF SATISFACTION ON SCALE FROM DISSATISFIED TO VERY SATISFIED, PLEASE COMMENT IF DISSATISFIED.

DATE / / 20	PATIENT CODE 1	UNDER-GRAD (29, 40.0 %) POST-GRAD (7, 10.0 %) CONSULTANT (24, 33.0 %) NON-CONSULTANT STAFF: FOUNDATION (6, 8.0 %) SPR (6, 8.0 %) SHO ◯ OTHER:
NEW PREPRATION (40, 55.5 %) REPLACMENT RESTORATION (28, 38.8 %) Combination of both (4, 5.7 %)	**TEETH** **8 7 6 5 4 3 2 1** **8 7 6 5 4 3 2 1** (127 teeth)	SINGLE UNIT CROWN (56, 70.0 %) BRIDGE (16, 20.0 %) Implant (1, 1.2 %) Inlay/Onlay (7, 8.8 %) Some cases had combined types of restorations
TECHNICIAN CODE	**SHADE** SELECTED BY TECHNICIAN	**(DISSATISFIED)** **(VERY SATISFIED)** **DENTIST TO MARK ON SCALE WITH A VERTICAL LINE HOW SATISFIED WITH THE SELECTED SHADE.** Mean 8.83, (min 3, max 10)

GINGIVAL CONDITION

POOR (6, 8.3 %) ACCEPTABLE (34, 47.3 %) EXCELLENT (32, 44.4 %)

PREPARATION (FINISH-LINE) (1 implant and 1 inlay)

SHOULDER	CHAMFER	DEEP CHAMFER	BEVELLED SHOULDER	KNIFE EDGE
(26, 36.1 %)	(22, 30.5 %)	(19, 26.0 %)	(3, 4.1 %)	(2, 2.7 %)

PREPARATION (FINISH-LINE AT DEEPEST ASPECT) (1 implant and 1 inlay)

SUPRA-GINGIVAL	SUB-GINGIVAL	AT GINGIVAL LINE
(18, 25.0 %)	(15, 20.8 %)	(39, 54.2 %)

CORE MATERIAL (some cores are combined materials)

AMALGAM	COMPOSITE	GI/RMGI	TOOTH	METAL
(7, 4.0 %)	(43, 40.0 %)	0	(31, 22.0 %)	(5, 5.0 %)

MORE THAN ONE CYCLE CAN BE TICKED.

IMPRESSION MATERIAL USED FOR PREPARED TEETH:

Silicone and wash (putty and light body)

FACE-BOW

YES (18, 25.0 %) **NO** (54, 75.0 %)

OCCLUSAL RECORD

YES (54, 75.0 %) **NO** (18, 25.0 %)

IF YES: **WAX** (8, 14.9 %) **SILICONE REG. PASTE** (46, 85.1 %) **MARKED INDEX TEETH** ◯

COMMENTS:

Figure 7.6 Questionnaire 1 (n = 72, 96.0 % response rate) with distribution of responses in red

Questionnaire 2 (laboratory technicians)

The second questionnaire completed by the laboratory technicians had the highest response rate (100.0 %). Five questions were asked in relation to the satisfaction with the information received from the dentist and these responses were graded on a ten point Likert scale 0 to 10, where 0 was very dissatisfied and 10 was very satisfied. All mean answers were above 9 which can be considered as very satisfied (Figure 7.7)

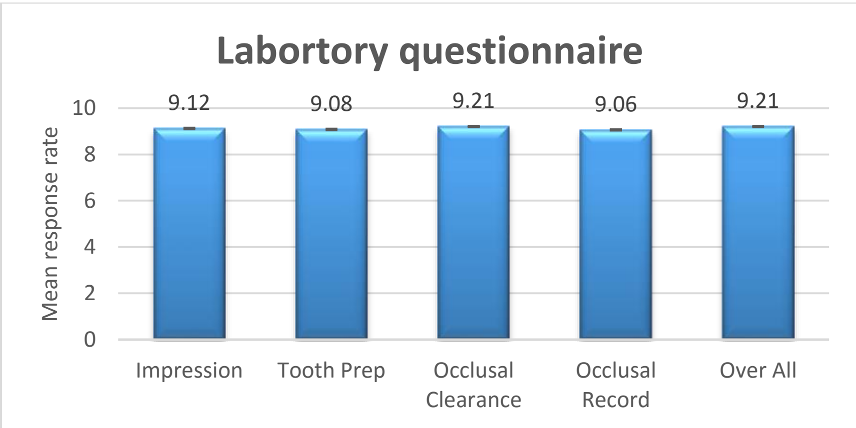


Figure 7.7 The mean value of the responses to the 2nd questionnaire questions.

Questionnaire 3 (Dentist at fit)

Seventy (93.3 %) questionnaires were returned by the dentists following fit of the restoration/s. In this questionnaire, eight questions were asked about the quality of the final restoration at the fit appointment, and again the satisfaction was recorded on the Likert satisfaction scale. The mean answers were all above 9 out of 10 with the exception of 1 question where it fell to 8.53 for occlusion. Whilst occlusion scored the least, this was for the restoration before the occlusal adjustments at try-in, after the restoration had been adjusted the score rose to a mean of 9.5 (Figure 7.8).

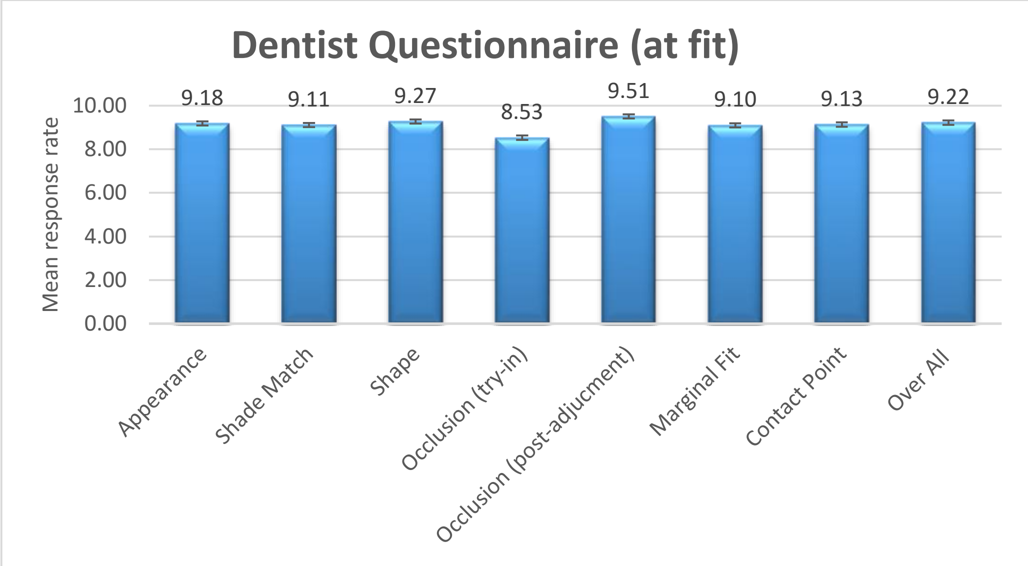


Figure 7.8 The mean value response rate of the 3rd questionnaire (Dentist at fit)

Questionnaire 4 (patient)

The fourth questionnaire was completed by the patient and related to their satisfaction with regard to their zirconia dental restoration. There were five questions asked in this questionnaire. All the responses showed high satisfaction rates with mean values above 9 being scored (Figure 7.9).

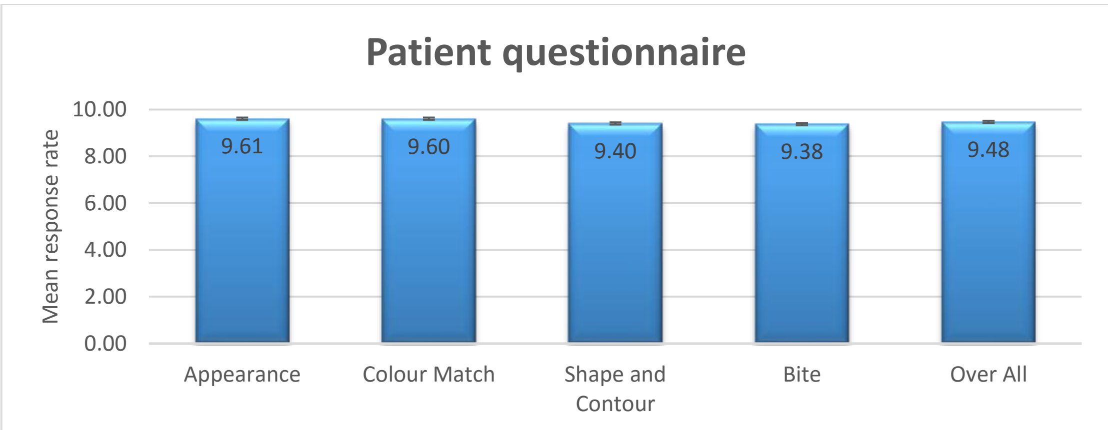


Figure 7.9 The response rate in the 4th questionnaire (patient)

Economical evaluation Gold prices

The price of gold had varied considerably over the last 5 years (2010-2014) with the mean gold price being £29.05/g (min £20.15/g and max £37.95/g) (Figure 7.10).

Figure 7.10 Gold prices from 2011 to 2015 (http://goldprice.org/)

Dental Restorations

Log books kept within the restorative laboratory at Dundee Dental Hospital and School, record the type of restoration made (and how many units) and the amount of gold used for each restoration in grams. Multiple jobs were occasionally cast at the same time from a larger quantity of gold. Only data clearly marked for one restoration was used. Data collected over the past five years (2011 - 2015) on 176 dental restorations were used to calculate the amount of gold needed for different types of dental restorations (Table 7.1) (Figure 7.11).

Table 7.1 The average gold weight used for different types of dental restorations (min and max), collected from Dundee Dental Hospital and School (2010 - 2014)

	Single crown	2 unit bridge	3 unit bridge	4 unit bridge	5 unit bridge
No. of rest.	50	50	50	21	5
Average (g)	2.96	3.77	8.04	9.68	14.03
Min (g)	0.6	1.2	3.3	3.1	10.8
Max (g)	7	7.6	15.7	17.7	16.7

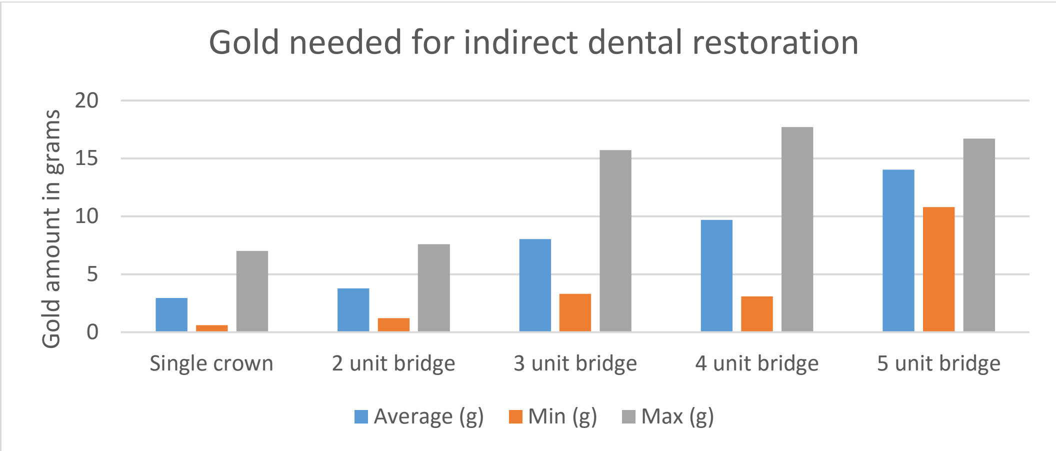


Figure 7.11 The average weight of gold (min and max) needed for dental restorations

Zirconia bridges / frameworks

A box of 6 Multi zirconia blocks cost £1068.73 (VAT) in 2015, each multi zirconia block costs £195. From each block four, three unit bridges (all zirconia) can be manufactured. Making the cost for each zirconia bridge/ framework £48.75. The number of bridges obtained from each zirconia block varies depending on the size of the crown, abutment or pontic. Table 7.2 is based upon the average dimension of anterior and posterior teeth.

Table 7.2 The different size zirconia blocks available, their prices and the number of units of indirect restorations that can be produced from each block.

Block size	Price (£)/ box	Units *	Price/unit
Lava 20	£263.98 (12 blocks)	2 Anterior Units or 1 posterior unit	£10 - £22
Lava 20XL	£171.39 (6 blocks)	2 Anterior Units or 1 posterior unit (long)	£14 - £29
Lava 40	£701.32 (12 blocks)	3 - 4 Anterior Units or 2 - 3 posterior units	£14 - £19
Lava 60	£1068.73 (12 blocks)	6 - 8 Units	£11 - £14
Lava Multi	£1068.73 (6 blocks)	10 - 12 Units	£14 - £17

*The number of units may vary depending on the size of the crown or bridge

Gold versus zirconia

Table 7.3 and Figure 7.12 shows the cost per unit for indirect restorations made from high fusing gold alloy at its lowest and highest cost over the last five years together with the cost per zirconia unit, manufactured from the multi blocks.

Table 7.3 The prices of dental restorations made from gold and zirconia

	1 Unit	2 Units	3 Units	4 Units	5 Units
Gold at £20	£59.20	£75.40	£160	£193.60	£280.60
Gold at £37	£109.52	£139.49	£297.48	£358.16	£519.11
Zirconia	£21.99	£29.22	£44.53	£89.06	£89.06

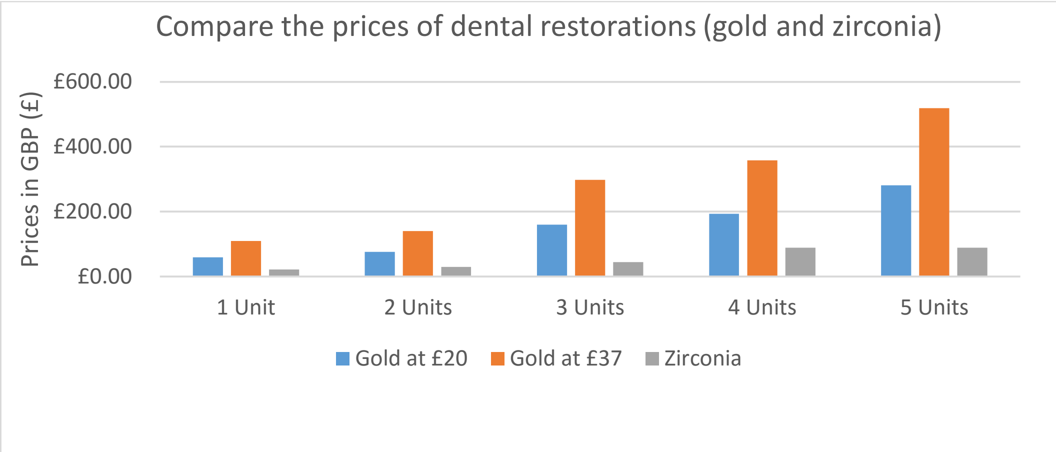


Figure 7.12 A comparison of gold prices versus zirconia for different dental restorations

For the most commonly provided restoration, a single unit crown, gold (at its cheapest) is 2.7 times more expensive than a zirconia restoration and, at its most expensive over the last 5 years, it is 5 times more expensive. When longer span bridges are concerned, for example the three unit conventional bridge, the differences in cost are 3.6 times and 6.7 times more expensive for gold based restorations (at its cheapest and most expensive respectively) compared to zirconia.

7.5 Discussion

Due to the lack of literature on dentist, dental technician and patient satisfaction with CAD CAM restorations, four questionnaires were designed to capture information on different aspects of different stages in the process of providing such a restoration. Two of the questionnaires were designed for the dentist, one to be filled in at tooth preparation and one at fit, one questionnaire was for the dental technician and one for the patient. The questionnaires were first piloted on the targeted population (dentists and dental technicians) to check for clarity and to ensure that all the aspects relevant to the preparation, fabrication and cementation of CAD CAM restorations were included.

According to Dillman, the response rate of questionnaires is calculated as follows: Response rate = No. of questionnaire returned X 100/ No. of all questionnaires issued (Dillman et al., 1984). In this survey 75 sets of questionnaires were issued, the overall response rate was generally good for dentists (n = 72 first questionnaire (96.0 %) and n = 70 second questionnaire (93.3 %)) and technicians (n = 75 (100.0 %)), however whilst the response rate was worse for patients (n = 58 (77.0 %)) it is still regarded as good and acceptable. The good response rate, of the dentist and technician questionnaire, is probably a result of having a “captive target population” within the Dental School with a vested interest in CAD CAM. However, the lower response rate of the patients, may be due to many factors such as, the dentist did not hand the questionnaire to the patients, time related issues for the dentist and patient or the patient simply was not interested in participating in the survey and filling in the questionnaire.

In relation to the first questionnaire the majority of the operators carrying out the tooth preparations were undergraduate students (n = 29 (40.0 %)) and consultants (n = 24 (33.0 %)) with smaller numbers of postgraduate students (n = 7 (10.0 %)), foundation trainees (n = 6 (8.0 %)) and StRs (n = 6 (8.0 %)). This distribution is entirely expected because the survey was carried out in a teaching hospital.

In relation to the type of preparation, new preparations were the most common (n = 40 (55.5 %)) compared with replacement restorations only (n = 28 (38.8 %)) and a combination of both (n = 4 (5.7 %). A chamfer finish-line is the recommended preparation margin for all ceramic restorations (Chadwick and Hall, 2011) and was the most commonly prepared margin (chamfer (n = 22 (30.5 %)), deep chamfer (n = 19 (26.0 %)). Closer examination of the questionnaires revealed that the majority of chamfer finish lines were obtained for the new preparations demonstrating that the operators were conforming to the taught standard or at least responding to the questionnaire with an answer which conforms to the taught standard. With hindsight, it would have been good to include the same question about margin configuration in the technician's questionnaire for comparison and validation. This having been said, the technician's satisfaction with the tooth preparations was high. The preparation of a shoulder finish-line was lower (n = 26 (36.1 %)), and this is due to the "inherited" finish lines in relation to the replacement restoration cases which would have mainly been metal ceramic crowns originally. It is difficult if not impossible to modify the old preparation and change it from a shoulder which was used for the metal ceramic restoration to a chamfer for the CAD CAM zirconia restorations.

Most of the prepared teeth were anterior, as CAD CAM restorations were chosen because they can produce highly aesthetic outcomes. In relation to aesthetics it is also important that the finish-line is equi-gingival, so that unsightly margins and root surfaces are not visible (Nugala et al., 2012). In this survey 39 (54.1 %) of the restorations had margins that were equi-gingival making them aesthetic and easy to clean (Khuller and Sharma, 2009). Lip or smile line is also important to take into consideration and this may explain why 18 (25.0 %) of margins were left supragingivally in cases where aesthetics cervically was less important in patients with a low smile line. This aspect could not be investigated through these questionnaires but since patient satisfaction with aesthetics was extremely high it is assumed that these supragingival margins were all acceptable.

When it came to the core material, composite was the most commonly used (n = 43, (40.0 %)), this can be explained by two points. Firstly, that composite was used as a filling material in that tooth and it acted as a restoration for some time, due to its high mechanical and aesthetic properties, making it the material of choice for restoring teeth (Cramer et al., 2011). Secondly, during the treatment planning phase a decision to restore the tooth with an all ceramic crown, would have dictated a tooth coloured material to prevent shine through of metal through the ceramic, hence composite being the ideal choice (Monticelli et al., 2005).

When the impression of the prepared teeth was carried out, almost all the participants used silicone impression (putty and light body). This is mainly because of the accuracy and stability of the silicone dental material. Digital imprisoning although it is becoming the impression of choice for some practitioners due to its specification and ease of use (Christensen, 2008), and was available for use at the Dental School, it was not used in any of the cases. This is because students were not trained to use the Lava COS. However the Consultant staff were all trained, but despite the fact that they accounted for 33.0 % of the restorations made in this survey, not one used the Lava COS scanner. The only explanations for the staff not using the intraoral scanner is the long time between the training and the patient's appointment the fact that the staff were trained at the under graduate level with conventional impressions making them more comfortable with this technique and finding it easier to use. Perhaps repeated continual training in the use of the scanner on phantom heads may raise the confidence levels with this new technique and hence the frequency of use.

The laboratory technician's questionnaire had the highest response rate (100.0 %), with high satisfaction rates (> 9 out of 10) for all questions asked. The high response rate is due to the fact that the technicians were central to the distribution of questionnaires in the laboratory. The high satisfaction rates for the technicians reflects the high quality of the clinical work carried out, because the dental technicians are essentially assessing the work carried out by the clinicians (the impression, tooth preparation, occlusal clearance and occlusal record (if provided)).

At the fit appointment, a questionnaire was completed in by the dentist in order to assess the restoration and evaluate the laboratory work carried out. The questionnaire covered different aspects, appearance, shade match, shape, occlusion (try-in), occlusion (post-adjustment), marginal fit and contact point. The results indicated high satisfaction rates (above 9 out of 10) in relation to all aspects of the restoration, with the exception of the occlusion (try-in) which scored 8.53 out of 10. Usually minor adjustments are required with most indirect dental restorations at the try-in stage (Wassell et al., 2002a), and CAD CAM restorations are no exception. Most of the restorations made would have been constructed using a zirconia coping or frame work veneered with ceramic, therefore the occlusal scheme is down to human judgment and may account for the satisfaction with the occlusion. This having been said, the satisfaction score of 8.53 may still considered high and the amount of adjustment required probably minimal. After the occlusal adjustment the satisfaction with the final occlusion, as assessed by the patient, rose to 9.51 out of 10.

The patient's questionnaire asked five questions relating to the appearance, colour match, shape and contour and bite; for all parameters the satisfaction rate was over 9. Previous patient satisfaction questionnaires have focused on the dental clinic, and dental team skills (Burke and Croucher, 1996, Newsome and Wright, 1999). More commonly, patient satisfaction rates have been investigated in retrospective studies, when the survival rate is investigated (Kan et al., 2003, Gotfredsen, 2004, Meijndert et al., 2007, De Rouck et al., 2008, Tartaglia et al., 2011, Shi et al., 2015). This is because patient satisfaction is also based upon restoration survival and longevity. Unfortunately the restorations in this audit cannot be followed up for longevity and traced back to the outcomes of the four questionnaires, as for an audit and Caldicott Guardian approval, all questionnaires have to be anonymised but this could be an interesting part of any further research.

Economical (cost) analysis is discussed widely but less commonly so among dental professionals or organisations (Walton and Layton, 2012). It is clear that discussing treatments and costs with patients is of a great importance, because patients might change their treatment options due to the cost. Therefore evidence of cost effectiveness of restorations important to inform dentist patient discussion on treatment options. In 2004 Kelly and Smales investigated the long-term (15 years) cost effectiveness of using direct restorations for restoring large tooth defects or indirect dental restoration (all metal or metal ceramic crowns) in private dental practices. They concluded that direct restorations were the most cost effective, followed by all metal and finally metal ceramic indirect restorations (Kelly and Smales, 2004). The results of this study were not surprising, as indirect restorations require more steps and materials which can be expensive. These results were based on the dentists' evaluation, but on the other hand, cost satisfaction analysis (at treatment and at follow up) of fixed prosthodontic restoration has been investigated among patients who have received this type of dental restorations within the previous 20 years by sending a questionnaire (VAS) to the patients. The results showed that, although the patients considered fixed dental prostheses to be expensive at the time of treatment, in the long run, they felt that they were good value (Walton and Layton, 2012). Such restorations may therefore be cost effective in the long term.

In this audit, the difference between the materials (gold and zirconia) used to produce indirect dental restorations were compared, mainly because gold has been the material of choice for many years, due to its superior specifications (Liviu Steier et al., 2007) and because high fusing gold alloy is the material of choice for metal ceramic restorations at Dundee Dental School. By monitoring the prices of gold in the last 5 years, it is clear that the prices fluctuate quite dramatically (min £20.15/g and max £37.95/g), this makes it difficult to predict the exact cost of an indirect dental restoration at any given time. This is also compounded by the size of any restoration. On the other hand zirconia blocks generally have a set price (although might be subjected to some price increase), making estimation of cost of zirconia based indirect dental restorations more predictable.

Using CAD CAM technology is more time and cost effective compared with conventional practice, as it can produce dental restorations in less time and less man hours (Lee and

Gallucci, 2013). Zirconia is also cheaper compared with gold restorations as can be seen from the results of this audit (where the material cost of gold based restorations could reach nearly five to six times that of a CAD CAM zirconia based restoration) and the study by Joda and Bragger (2015), where the cost of CAD CAM implant restorations are compared with conventional implant prostheses. The results showed that the cost of the digital workflow was significantly lower than that of the conventional workflow, regardless of the price of the implant (Joda and Bragger, 2015).

It is ironic therefore that in private practice CAD CAM restorations cost more than gold based restorations. This is probably due to the high start-up cost for the technicians in buying the scanners and in particular the milling machines but could be overcome by a number of laboratories/technicians having a centralized milling center. The return rates for the questionnaires in this audit were generally good and satisfaction rates high from all participants, but the results may have been very different if the same audit was carried out in a busy private practice where time is inextricably linked to cost (unlike in a teaching hospital) and perhaps greater patient expectations when paying large bills.

7.6 Conclusions

Within the limitation of this audit and results, the followings can be concluded:

1. Dentists and dental students are familiar with the preparation of zirconia based restorations.

2. The tooth preparations, impressions and laboratory work were of a high standard at Dundee Dental Hospital.

3. The patients were highly satisfied with the final outcome of the zirconia based dental restoration.

4. Zirconia based restorations were more cost effective in the short term.

Chapter 8

Conclusion and further work

8.1 Principal Findings and further work

The principal findings of this PhD thesis are:

1. Lava COS and Lava CAD CAM system (Lava™, 3M, ESPE), produces highly precise and highly aesthetic indirect zirconia based restorations.

2. Dentists apply different forces during cementation of indirect dental restorations, the highest force being applied in the first 30 seconds, then dropping to a lower consistent force with time. Despite the differences in force applied there was no impact on accuracy of fit.

3. Additional firing cycles used with veneering ceramics onto zirconia frameworks can lead to a significant increase in internal and marginal gaps (fit).

4. Increasing the span length of all zirconia bridges is unlikely to have an impact on the internal and marginal fit of the all zirconia bridges.

5. Zirconia based restorations (all zirconia, veneered zirconia frameworks and un-veneered zirconia frameworks) can withstand forces in excess of occlusal forces normally achieved by patients in both the anterior and posterior regions of the mouth. Whilst veneering a zirconia framework increases the strength of the frameworks, the all zirconia restorations were the strongest.

6. The audit showed that, at Dundee Dental Hospital and School both dentists and dental students are familiar with zirconia based restoration tooth preparation, this was followed by a high standard and quality of the impression and laboratory work resulting in dentists and patients being highly satisfied with the final zirconia based indirect dental restoration provided. The cost analysis showed that zirconia based restorations are five

to six times cheaper than gold alloy based restorations, but we need to have in consideration the set-up cost of the CAD CAM system.

8.2 Further work

Further work could be carried out to:

- investigate the seating pressure applied to different types of CAD CAM restorations (different span bridges with differing configuration (curved arch or straight span), veneers, inlays and onlays) using different types of luting cements with different viscosities, and the impact that would have on fit.

- investigate the effect of veneering and firing cycles on the fit of zirconia based restorations with full firing cycles (e.g. sintering, de-waxing, ceramic pressing, glazing and finishing).

- investigate the effect of different types of veneering ceramics and different veneering techniques (e.g. pressing, conventional, CAD on) on the fit and strength.

- investigate the strength of zirconia based restorations using different span lengths, different configurations and different connector diameters and different thickness of zirconia based restorations.

- investigate the accuracy of different types of conventional impression materials and techniques can be compared with different types of digital impression systems.

- repeat the audit but with a tracking code, to allow investigation of the survival and longevity of the restoration and to compare this with the satisfaction of the patient and dentist in the long term.

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Appendix 1

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CONFIDENTIALITY STATEMENT - for users of person identifiable data

User Details	
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Sponsor Details	
Name:	Professor David Ricketts
Position:	Prof. Cariology & Conservative Dentistry & Hon. Consultant in Restorative Dentistry
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Tel:	01382 635984 d.n.j.ricketts@dundee.ac.uk

Data Protection Reg. No.	
Data Requested :	CAD/CAM Restorations Audit
A Data Processing Specification must also be completed.	To issue a set of four questionnaires to dental patients, dentists, and technicians who are to deal with dental restoration relying on CAD/CAM techniques for the fabrication of ceramic crowns or bridges. The data gathered through the questionnaires will be used to evaluate patient's, dentist, and technicians levels of satisfaction in the process and the finished product. Measurements will be also made on anonymised models of the prepared teeth to assess how the teeth have been prepared.
Co-Users of the Data :	The nurse or dentist involved in the patient treatment will issue the questionnaires.
Intended use of data (inc. publications) :	Audit and evaluation of CAD/CAM techniques, and patient satisfaction with process and product. Intention to produce publication of findings.

User's Declaration

I declare that I understand and undertake to abide by the rules for confidentiality, security and release of data received from NHS Tayside.

Signature

Date 27-6-2011

Sponsor's Declaration (to be signed by a consultant if patient data is requested and the applicant is not of that status or is not medically qualified)

I declare that the above named user of the data is a bona fide worker engaged in a reputable project and that the data requested can be entrusted to this person in the knowledge that they will conscientiously discharge their obligations in regard to confidentiality of the data.

Signature

Date 27/6/11

On completion, please return this form to:

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Ashludie Hospital

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Approved by the
Medical Director
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Nawaf Almustafa
PhD Student
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Dear Sir/Madam

Caldicott Approval – CAD/CAM Restorations Audit

Attached to this letter is a copy of the completed Confidentiality Statement giving Caldicott Guardian approval for the transfer and use of data as described in your statement.

Thank you for your co-operation in providing us with the information requested by us in this process.

Please contact me should any queries arise from the application of this approval.

PP AH
Peter McKenzie
Information Governance Manager

Cc: Professor David Ricketts, Professor of Cariology & Conservative Dentistry
file

Headquarters
King's Cross, Clepington Road, Dundee DD3 8EA

Chairman, Mr Sandy Watson OBE DL
Chief Executive, Professor Tony Wells

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RULES ON CONFIDENTIALITY, SECURITY AND RELEASE OF INFORMATION

FOR USERS OF NHS PATIENT DATA

1) If the data received from NHS Tayside are to be held on computer, the signatory of this request, or the organisation (s)he represents, should have an appropriate registration with the Office of the Data Protection Registrar. Details of the registration number should be entered on this document.

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NHS Tayside would welcome copies of any publications based on data supplied.

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